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Climate customized techno-economic analysis of geothermal technology and the road to net-zero energy residential buildings

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Individual and societal desires for fossil-fuel independence are an increasingly popular goal. This research investigates residential geothermal space heating and cooling as a viable technical and financial alternative. The road to net-zero energy is then assessed, weighing the benefits and detriments to the consumer.

First, the template for location-specific geothermal space heating and cooling is developed through a pilot analysis of a home in Memphis, Tennessee. A methodical process of soil investigation, prototype home characteristics, and financial incentives is designed. Expanding upon existing studies, accurate soil data is extracted from beneath the foundation of a specific address, rather than region-wide soil averages. This high level of precision allows the owner of a specific address to preview realistic results and develop truthful expectations. Payback period and system lifetimes savings are calculated using two methods.

Second, the framework developed through the Memphis, Tennessee pilot home is used to investigate 11 additional cities across the continental United States. The increase in breadth uses a representative city from its respective climate zone. While each city within a single climate zone will vary from the representative city, a general climate performance can be determined. With each

location's soil properties and heating and cooling demands, the borefield design and heat pump system capacity is customized and applied for analysis. Using human interest surveys from previous energy projects, a climate is ultimately classified as viable or nonviable for geothermal heating and cooling.

Finally, the increasingly popular net-zero energy building concept is explored through a complementary solar photovoltaic (PV) array to the geothermal system. An array capacity is sized and priced to offset the total facility energy use in each climate's representative city. Once determined, the payback and lifetime savings values are calculated and the GHP + PV system results are compared to a baseline + PV system. From this, a system type is identified as the more viable option for each of the 12 climate zones. The final touch on this research is the introduction of the human perceptions toward environmentally friendly renewable energy in general and how it affects a consumer's ultimate decision.

DEDICATION

This dissertation is dedicated to my Granddaddy, Mr. Charles Ford, the eternal engineer and inspiration for much of my higher education. In addition to an accomplished civil engineer, his 93 years of life was celebrated as a devoted husband and father, barbershop quartet singer, home designer and builder, and loving grandfather and great-grandfather. His timeless patience was inspiring. I know he will read this work in heaven – and I hope he enjoys!

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NOMENCLATURE

α	ground thermal diffusivity
θ	soil volumetric water content
θ_s	saturated soil porosity
ρ	soil density
AHU	air handling unit
AOI	area of interest
APP	actual payback period
AS	annual savings
Btu	British thermal unit
C_k	soil conductivity classification
c_p	ground specific heat capacity
Cap	heat pump nominal capacity
Cap_{HP}	heat pump cooling capacity
CDD	cooling degree days
CHP	combined heat and power
COP	coefficient of performance
COP_C	cooling coefficient of performance
COP_H	heating coefficient of performance
$Cost_{ca}$	initial capital cost after incentives

$Cost_{cb}$	initial capital cost before incentives
$Cost_{cb,GHP}$	initial capital cost before incentives, GHP system only
$Cost_{cb,PV}$	initial capital cost before incentives, PV system only
$Cost_{cb,Total}$	initial capital cost before incentives, GHP + PV system
$Cost_{e}$	electricity cost
$Cost_{n}$	balance remaining after *n* years
DPP	discounted payback period
DSIRE	Database of State Incentives for Renewable & Efficiency
DX-GSHP	direct expansion ground source heat pump
E_{cons}	energy consumed by facility
E_{gen}	energy generation by PV array
E_{pur}	energy purchased from grid
E_{sold}	energy sold to grid
ECM	electronically commutative motor
EE/NZE	energy-efficient/net zero energy
EER	energy efficiency ratio
EUI	energy use intensity
°F	degrees Fahrenheit
f_{10y}	correlation function for 10y
f_{1m}	correlation function for 1m
f_{6h}	correlation function for 6h
ft	feet
GDH	geothermal district heating

GHC	geothermal heating and cooling
GHE	ground heat exchanger
GSHP	ground source heat pump
h_{conv}	convective film coefficient
HDD	heating degree days
HDPE	high-density polyethylene
HGSHP	hybrid ground source heat pump
HP024	2-ton capacity heat pump
HP036	3-ton capacity heat pump
HP048	4-ton capacity heat pump
hr	hour
HVAC	heating, ventilation and air conditioning
i	rate of inflation
i_M	incentive structure strength multiplier
i_{max}	maximum incentive structure strength
i_s	solar irradiance [kWh/m^2/day]
in_i	incentive i
j	discount rate
J	Joule
k	soil thermal conductivity
K	Kelvin
k_{grout}	grout thermal conductivity
kg	kilogram

kWh	kilowatt-hour
L	borehole length
L_U	center-to-center distance between pipes
Lifetime Net	total system lifetime savings
m	meter
m_{fls}	total mass flow rate/kW of peak hourly ground load
MLS	Multiple Listing Services
n	year post-investment
NREL	National Renewable Energy Laboratory
NZE	net zero energy
NZSEB	net zero site energy building
OA	outside air
q_y	hearly average ground heat load
q_m	highest monthly ground heat load
q_h	peak hourly ground heat load
R_{1m}	effective ground thermal resistance corresponding to 1 month
R_{6h}	effective ground thermal resistance corresponding to 6 hours
R_{10y}	effective ground thermal resistance corresponding to 10 years
R_b	effective borehole thermal resistance
r_{bore}	borehole radius
R_{conv}	convective resistance inside tube
R_g	grout resistance
R_p	conduction resistance inside tube

$r_{pipe,ext}$	outside radius of pipe
$r_{pipe,int}$	inside radius of pipe
R_s	sun intensity rating
RA	return air
RH	relative humidity
S_i	incentive structure strength factor
S_r	degree of soil saturation
SC	space cooling
SPP	simple payback period
T_g	undisturbed ground temperature
$T_{in,HP}$	max/min heat pump inlet temperature
T_m	mean fluid temperature in borehole
T_{OA}	annual average air temperature
$T_{OA,max}$	maximum difference in monthly average air temperature
$T_{out,HP}$	max/min heat pump outlet temperature
T_p	temperature penalty for multiple boreholes
TMY	typical meteorological year
TVA	Tennessee Valley Authority
WAHP	water-to-air heat pump
W	watts

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CHAPTER I

LITERATURE REVIEW

1.1 Introduction

Knowledge of the long-term benefits of geothermal technology has the potential to empower the residential sector at large and the financial health of individual consumers. Benefits include both energy and financial savings by replacing existing space heating and cooling systems with geothermal systems. There is no shortage of the technical assessments of geothermal energy for space heating and cooling, in both the commercial and the residential sector of the United States and abroad. From the perspective of energy savings, the argument is quite compelling to tap into this available and inexhaustible heat sink below the surface of the Earth. However, before the energy savings, the system must be constructed – an endeavor that only becomes possible with a substantial initial monetary investment. With data comes knowledge, and knowledge is the tool necessary for savvy homeowners to feel confident in a change of technology.

Despite the proven benefits of geothermal energy use in the residential sector, much work is still needed to make the option affordable and accessible. The review of published data will outline barriers to widespread deployment of renewable energy (RE) systems, system simulation, design optimization, life cycle cost analysis, and financial incentive analysis. Sources within encompass both the United States (U.S.) and international history of activities.

Lessons learned from prior and current research teams provide direction toward identifying and developing further investigations. Main objectives include financial benefits, involvement in the renewable energy revolution, and contributions to the quality of life improvement of homeowners.

1.2 Growth and Factors Prohibiting Widespread Adoption of Renewable Energy Systems

Abundant research on residential ground source heat pump (GSHP) systems claims high initial cost is the main barrier for widespread adoption in both commercial and residential sectors [1]–[6]. Despite tax rebates, incentives, loan programs, and future energy savings, the initial high cost of ground heat exchangers (GHE), drilling, and other equipment is too high for many homeowners.

In addition to measurable factors prohibiting widespread growth of renewable energy systems, research highlights the less tangible factors of 1) public education and 2) federal support consistency. Thorsteinsson and Tester [7] conducted a revealing survey study that assessed the public awareness of geothermal resources. While the focus of the research had geothermal district heating (GDH) as the ultimate target, the outcome of the awareness assessment can be applied toward general public and homeowner awareness. The findings concluded that 60% of community leaders admitted to ignorance about how and where to gather information to pursue GDH heating systems in their locales. Even though many are aware of the economic and environmental benefits, the obstacles are too daunting for community leaders to invest the time and effort. Programs to educate United States about geothermal resources have come and gone, such as *GeoPowering the West* by the U.S. Department of Energy (DOE). This expired program aimed to address the educational deficits across western states for geothermal energy and electricity generation. The fact that *GeoPowering the West* is no longer active supports the inconsistency claim of federal support. Whether for district heating systems or residential deployment, federal funding programs have cyclically surged and retreated. Loans, grants, and congressional acts have provided a few western states enough financial support to implement GDH systems. Changes to research program funding, geothermal land-leasing, and state legislation regulations have also contributed to the blockade between individuals and mature geothermal energy implementation. Thorsteinsson and Tester [7] thoroughly identify the highs and lows of geothermal education, funding, and ultimate execution.

Fear of the unknown is another intangible barrier to geothermal development, both individual or community in scope. Reber et al. [8] presented a unique perspective on the primal aspect of resistance to change. Unlike other forms of renewable energy such as solar and wind, geothermal energy cannot be seen by the human eye. One can see the sun and the motion of a wind turbine, but not see into the deep underground. This inability to be experienced through senses causes human beings to hesitate and resist adoption of novel technology. Therefore, Reber et al. [8] recognizes human perception as a barrier to widespread geothermal development.

Internationally, the surge in efforts to exploit this valuable renewable energy source is apparent. As of a 2011 geothermal energy use survey worldwide, China, United States, and Sweden ranked in the top three nations for direct geothermal use. Within the European Union, the prevalence of geothermal use grew by 25% from 2011 to 2012. According to Păceşilă [9], the European Union National Renewable Energy Action Plans (NREAP) aimed to increase the capacity of geothermal networks by 20% from 2012 to 2020. Similar to other countries and sectors, however, the growth may be halted by the initial investment of geothermal infrastructure. Government strategies are in place to assist with financial burdens such as feed-in-tariffs, tax benefits and other government subsidies. Feed-in-tariffs are monetary payments to individuals that do generate their own electricity through renewable sources. Most of this activity, however, encompasses high enthalpy geothermal sources that is used to generate electricity from heat, rather than convert to heating and cooling. These applications apply less to homeowners and more to plant operations.

Money is not the only barrier to geothermal system growth internationally. In Germany, despite the implementation of numerous policies, a revealing study by Michelson and Madlener [2] pointed to human and home-driven growth deterrents. The research team focused on the characteristics of the homeowner and the residence to quantify a likelihood of renewable heating system adoption. They attempted to predict the decision-making process of the homeowner. Interestingly, the income, level of education, age, and gender of the homeowners were human variables considered in the probability equation. Home characteristics such as age of home, type of existing heating system, customization of home architecture, and geographical location in Germany were home variables in the probability equation. While not a comprehensive list, these factors represent the subjective spectrum of homeowner and residence characteristics that influence renewable energy adoption. Despite the government policies attempting to mitigate high initial costs, these subjective factors may ultimately sway homeowners one direction or the other.

In the Greek residential sector, Karytsas and Choropanitis [3] reported the results of the Domestic Use of GHSPs in Greece public survey. The survey attempted to pinpoint the major barriers for widespread GSHP adoption in Greece. Three of the top blockades were 1) installation cost, 2) insufficient public knowledge of GSHP systems and its benefits and 3) land area constraints in urban areas. The response to the survey results will be discussed in Section 1.5.

1.3 Materials and Methods Used for Simulation Energy Use

Lui [1] performed a study with both commercial and residential building types. The scope of the research was twelve (12) climate zones across the United States. The prototype home chosen for the simulation was a single level, slab-on-grade home with wooden framing. This home was used for all twelve (12) climate zones as representative of the typical residential dwelling in the U.S. Simulation objectives were to satisfy the home's space heating and space cooling demands, comparing the existing HVAC system to a GHE system with a water-to-air heat pump. One of Lui's main findings was that the energy savings was highly dependent on the home's existing HVAC system type, efficiency, and source. The simulated residence condenser consists of ground heat exchanger with designed vertical bore. It is unknown whether the bore was redesigned for each climate zone, based on geographical ground parameters. The review reveals between 32% and 59% annual energy savings for single family residences, a consistently higher result that for commercial buildings. As is performed in this research, Lui [1] states that more accurate energy savings data may be obtained by customizing the ground heat exchanger through geographically specific ground characteristics. Clear strengths of the report are the identification of diverse climate zones and comparison of existing HVAC systems to geothermal heat exchanger systems, in terms of energy savings. Topics of elaboration consist of, but are not limited to, site-specific prototype models for simulation, GHE design based upon site ground characteristics, and payback period analysis for retrofit applications. Local electricity cost data will provide valuable information on payback, and how viable a geothermal retrofit will be for inhabitants of study regions. Lui's [1] study is the source of the cited cost of residential geothermal system installation of $3,000 - $5,000 per ton of cooling.

Lim et al. [5] conducted an analysis residential geothermal heat pump systems, suggesting improvements that could yield more accurate results. Within the scope of simulation methods, the research team used data from the Residential Energy Consumption Survey (RECS) to group residences by climate region and state. From this energy use data, heat pump equipment was sized.

However, specific building characteristics were not considered such as year built, insulation type, fenestration type, construction envelope, number of occupants, or site-specific weather patterns. Lim et al. [5] stated that better energy use inputs would result from EnergyPlus™ or a comparable simulation engine, as well as region-customized home characteristics.

1.4 Design Optimization for Residential Geothermal Systems

Through the design optimization process, multiple factors can affect the performance, efficiency, and ultimate energy savings of a residential ground source heat pump system. An immensely valuable study by Eslami-Nejad et al. [10] compared air-source, ground-source, and hybrid heat pumps for energy use in cold climates. Montréal, Canada is the location of the subject home. Through the comparison of these three types of heat pumps, several parameters were modified on the ground loop and heat pump capacity to distinguish optimal performance. The study assumed a stainless-steel borehole U-tube rather than the more traditionally used high density polyethylene (HDPE) in the United States. Also, only the heating mode was considered. While the main objective was to determine whether a hybrid type heat pump resulted in significant energy savings, the most useful information relevant to this study was the parametric analysis of the direct expansion ground source heat pump (DX-GSHP) configuration. A hybrid ground source heat pump system (HGSHP) consists of the ground loop evaporator as well as an additional air-source evaporator to meet extreme temperature situations. The air evaporator only functions once the ground loop returns fluid at a temperature too low to meet the heating demand. Through multiple configurations of heat pump sizing, borehole quantity and length, borehole diameter, and pipe diameter and thickness, a detailed comparison emerged identifying optimal design parameters for the Montréal-specific climate. The authors' conclusions reinforced the importance of proper ground loop and heat pump sizing for maximum efficiency and performance. They determined that, with proper sizing of the ground source heat pump system, the inclusion of a hybrid evaporator did not significantly reduce energy use over the calendar year. Undersized systems, however, will spike electricity use. Therefore, Eslami-Nejad et al. [10] suggested erring on the side of an oversized heat pump. The argument claims that a slight increase in initial investment for a larger heat pump can be quickly offset by the annual increase in consumption savings. The life-cycle cost analysis is stated as the next step of the revealing study.

A residential application was considered in Athens, Greece where borehole depth, quantity, and software type to determine efficiency through measure of circulating fluid mean temperature. Sagia et al. [11] concluded that proper sizing of the ground heat exchanger is the vital factor to effective simulation and performance. In their study, the control case was a 3-borehole quantity loop of 70 meters in depth. The borehole quantity remained the same, but lengths increased incrementally by 10 meters to a maximum depth of 140 meters. Borehole spacing was also varied. Results confirmed that larger borehole spacing creates less heat transfer interference and thus a higher mean fluid temperature. Undisturbed ground temperature was estimated from average air temperature, and the source of the ground thermal conductivity data point was not revealed. Unlike the study by Sagia et al. [11] , this research attempts to improve upon the estimations of ground temperature and ground conductivity through geographically pertinent soil properties.

Additional design features that have major potential to improve system performance include ground loop pipe characteristics, installation site investigations, and system controls. The history of the ground loop featured metal tubing, but when it proved susceptible to leaking and maintenance issues, the design choice evolved to high density polyethylene (HDPE). Spitler [11] reported on a thermally enhanced grout (TEG) and HDPE pipe and its effect on required borehole depth for equivalent performance to the baseline case of bentonite grout and standard HDPE. With various combinations, the study revealed a reduction in required borehole depth of 27% with the use of both the TEG and enhanced HDPE pipe. Mechanical spacers between U-tube legs to push pipes to the outer radius of the borehole also showed promise in optimizing heat transfer to and from the ground. However, the spacer installation increase construction costs and offset the energy savings potential. For controls, emphasis was placed on shutting off the fluid circulating pump when the heat pump was not operational. In another publication, Spitler [12] emphasized the importance of the ground heat exchanger and heat pump integration during the design process to achieve efficient performance. Proper length of the ground heat exchanger, as well as choosing the optimal size of heat pump can greatly improve system performance. Both components of this loop are critical, and they work together effectively if proper system integration is considered in design. Proper GHE design also requires ground thermal conductivity characteristics. For commercial projects, ground samples can be extracted for accurate conductivity data. However, the cost of these *in situ* extractions may be cost prohibitive for residential projects. Recommendations are not included for the most effective methods to determine ground thermal properties for residential designs.

Location-specific ground characteristics such as soil conductivity were not considered by Lim et al. [5] in their residential geothermal heat pump due to lack of available information. However, this study published extremely valuable land area requirements and cost data through extensive interviews with geothermal system construction experts [5]. Dhepe and Krishna [13] also published land area requirements as a function of cooling load required. For consistency, the data reported have been converted from [m^2] to [ft^2]. Results are summarized in Table 1.1.

Table 1.1 GHE Installation Data

Borefield Type	Land Requirements	Installation Cost
Vertical	100 – 300 ft^2/ton 248 – 291 ft^2/ton	$ 4,400/ton
Horizontal	1,500 – 3,000 ft^2/ton 2,497 ft^2/ton	$ 2,640/ton

Karytsas and Choropanitis [3] analyzed the Greek residential GSHP sector. The sector is heating dominant with fossil fuel heating source and electricity for air-conditioning [3]. Findings report that proper GSHP design heavily relies on climate, building characteristics, loads, and soil conditions. Soil characteristics are deemed the most important variable for GHE design and use of a Thermal Response Test (TRT) is recommended for best results. The research also presented cost data for varying GSHP characteristics in four climate zones throughout Greece, itemized by component for varying GHE configurations.

1.5 Prior Attempts to Calculate Life Cycle Cost for Geothermal Systems

Despite abundant published research and evidence, widespread adoption of geothermal space heating and cooling systems is stilted in residential buildings in the United States. Data reveals that only 0.5% of residential dwellings use GSHP systems for space heating and cooling [5]. The tangible main cause of delayed implementation is high investment payback periods, or the time required to recover the initial cost with annual savings. T. Lim [14] researched barriers to widespread adoption of geothermal residential heat pump systems. In the investigation, a simple payback (SPP) period was the method that calculated these payback periods. The SPP does not consider the time value of money.

Similar to a payoff period, Reber et al. [8] define the Levelized Cost of Heating (LCOH) metric for GDH systems. LCOH is a dollar amount per 10^6 Btu quantifying the cost per unit of energy required to pay off the initial capital investment by the end of the system lifetime (assumed 30 years). Their study analyzed a variety of locations around the U.S. that are viable places for GDH development. Through the research, it was concluded that slight changes to the discount rate used in the discounted cash flow formula caused highly varied LCOH results. Therefore, discount rate is a highly sensitive parameter in payoff determinations. The discount rate is used for individual, residential applications as well as the community-wide GDH applications.

Only federal incentives were considered in Lim et al. [5], due to the variability of local programs and unavailability of all local information. However, the authors suggested a more accurate payback period can be calculated if local state and community incentives are included and payoff analysis.

Internationally, Karytsas and Choropanitis [3] determined payoff of GSHP system costs and maintenance for homeowners in Greece. An installation estimate is used for cost per kW of energy for GSHP components including GHE, heat pump, distribution, and engineering costs. For a closed loop GSHP system to replace a natural gas heating / air-source-heat-pump cooling, the estimated payoff ranges from 7.18 years to 10.67 years, depending on the climate zone.

In an effort to quantify the number of interested homeowners, Karytsas et al. [15] conducted polls of homeowners to answer these very questions about energy saving space heating and cooling systems. Although conducted in European countries, the results are a reputable gauge on how consumers would respond in the United States. The data presented in Table 1.2 display the percentage of citizens surveyed willing to accept certain payback periods.

Table 1.2 Percentage of Homeowners Willing to Accept Payback Periods

Country	0 – 5 Years	5 – 8 Years	8 – 10 Years	10 – 15 Years	15+ Years
Greece	69%	16%	8%	3%	4%
Spain	59%	13%	15%	3%	6%
Portugal	71%	11%	12%	1%	5%
Average	**66.4%**	**13.4%**	**11.7%**	**2.4%**	**5.0%**

Several approaches have been executed in prior research of energy projects to determine payback. Each method has advantages and disadvantages depending on the analysis objectives.

1.6 Existing Incentive Analysis for Renewable Energy Systems

1.6.1 International Incentive Analysis

Across the Earth, Karytsas and Choropanitis [3] reported that only 26 countries had residential GSHP systems in 2000 and that number rose to 48 countries by 2015. In Greece, the historical timeline of incentives is erratic. Between 2004 and 2014, incentives cyclically ranged from zero assistance to interest-free loans and grants. As introduced in Section 1.2, the Domestic Use of GSHPs in Greece survey was administered. The barriers to widespread domestic use are stated previously. To address the public opinion, those surveyed were asked what actions would help curtail the barriers to widespread growth. Three of the top actions that the public indicated they would respond to were 1) different electricity prices for GSHP systems, 2) increased public awareness of system benefits and 3) tax exemptions.

Terzić et al. [16] reported that a GHE/heat pump system reduces the reliance on traditional energy sources by 50% in the European Union. Therefore, a sensible and financially possible development scheme is just as desired internationally as is domestically. As the United States, however, the best method to achieve growth in the renewable energy sector requires financial incentives and creative schemes.

A unique perspective presented by Dumas [17] on how renewable energy, geothermal specifically, deployment is planned for the European Union. Through the development of "smart cities and smart rural communities", the European Union (EU) plans to drastically reduce the 80% of heating and cooling that relies on fossil fuels. These smart communities, outlined in the European Commission's Energy Roadmap 2050, will centralize heating and cooling with main renewable heating and cooling (RNC) plants [18]. The customers of the district heating and cooling plants will be connected through a network, much like an electricity grid, and will enjoy competitive energy rates. While this centralized concept will remove the initial capital investment cost off the end-user, or homeowner, the first obvious question concerns the funding for the grid and energy source infrastructure. Taxes for both users and non-users, as well as operational taxes may prevent the smart grid concept from widespread popularity.

In Germany, Michelson and Madlener [2] outlined several policies and programs that aimed to assist with capital investment of renewable energy systems to comply with *Energiekonzept*. *Energiekonzept* is the country's plan to reduce the residential sector's energy demand by 80% by the year 2050, and replace the remaining energy source need with renewable sources. Low interest loan programs, grants, feed-in tariffs and state subsidies were born from this plan. Act on the Promotion of Renewable Energies in the Heat Sector, Market Incentive Program, and Energy-Efficient Refurbishment Program are a few of these attention-grabbing efforts. While attractive by name, many of these programs were inconsistent with varying monetary awards by home type, source type, and calendar year. However, their implementation did assist some homeowners toward the 2050 *Energiekonzept* goal.

1.6.2 Domestic Incentive Analysis

Research widely agrees initial capital cost is a major barrier to GSHP growth in the United States. Innovative strategies aim to break down the cost barrier. “Loop-leasing” is a method described by Kavanaugh [4] wherein an investor funds the installation of the GHE system, then leases it back to the facility occupant for a monthly fee. An interesting concept, making most sense in the commercial or industrial setting. However, an analogy to the residential sector is not an impossibility. Rather than an individual investor, a lender or bank could offer low interest loans for initial capital investments for renewable energy home improvements. While Kavanaugh focuses on the commercial sector, a valuable model emerges with the “loop-leasing” approach. With modifications to fit the homeowner/lender relationship, an attractive financial opportunity may lure homeowners toward renewable energy system implementation. These creative financing strategies aside, there are several federal and local incentive programs throughout the U.S. Looking at programs from a broader scope, this section outlines domestic initiatives to provide financial incentives to homeowners for everything from light bulbs to large home energy projects.

1.6.2.1 ENERGY STAR Financial Incentive Program

ENERGY STAR certification includes satisfying rigorous requirements, completing a comprehensive inspection and approval process, and ultimately qualifying for financial incentives. Features of ENERGY STAR Certified Homes include high-efficiency heating and cooling, water protection system, complete thermal enclosure, and efficient lighting and appliances [19]. High-efficiency heating and cooling equipment used in ENERGY STAR Certified homes offer minimum noise emission, deliver premium indoor air quality with fewer pollutants than traditional systems due to continuous air filtration, and use overall less energy. The design of the HVAC system focuses on proper equipment sizing to ensure proper temperature and humidity control, as well as equipment life. System Installation optimizes duct design, proper sealing, and system testing.

A whole house water protection system is a critical component of healthy indoor air quality and structure longevity [20]. Minimal amounts of water infiltration into the home can ultimately lead to mold and material degradation, both leading to potential health risks and financial burdens. Construction materials, vapor barrier installation, and proper site drainage are major components of achieving the water protection for the ENERGY STAR Certified home.

Proper air sealing, sufficient levels of insulation, and the proper installation of insulation are the main requirements for ENERGY STAR Certified homes to achieve complete thermal enclosure [21]. Air leakage can drive up monthly energy costs due to warm or cool conditioned air escaping to the exterior of the home. Builders attempt to minimize thermal bridging, which is the presence of pathways that allow for heat to traverse between inside and outside. Continuous wall insulation between wooden studs or prevention of excess stud installation assist with this effort. Proper insulation installation and highly-efficient window selection and installation are also significant aspects of providing a complete thermal enclosure.

ENERGY STAR lighting and appliance technology has evolved to the point of ultimate comfort and cost savings. In addition to long life, cost savings due to drastically reduced energy use, and supreme safety ratings, light bulbs now can even reduce heat emitted during use. A LED 7-watt bulb manufactured by General Electric replaced a 60W bulb and does not get hot to the touch when illuminated. Therefore, the user saves money on lighting, as well as reduces the cooling load due to heat generation from bulbs. Appliances that have met ENERGY STAR Certification can significantly reduce the monthly utility portion that comes from dishwashers, clothes washers/dryers, refrigerators, and fans [22].

Upon completion of energy improvements, a rigorous inspection process ensues to satisfy the Environmental Protection Agency's (EPA) performance guidelines. There are four steps required to earn the label of ENERGY STAR Certified Home:

Step 1. Builder must be an ENERGY STAR partner

Builder makes a commitment to build new homes that satisfy stringent guidelines set forth by ENERGY STAR.

Step 2. Builder and Rater collaborate to choose energy efficient home features

Rater must approve construction plans and those plans are reviewed based upon the EPA developed prescriptive energy efficiency package.

Step 3. Builder builds home and rater field verifies and performs QA

Inspections performed frequently during construction due to the higher energy standards. Raters use a comprehensive checklist to verify home efficiency and inhabitant comfort.

Step 4. Rater certifies home and issues ENERGY STAR label

Final inspection is completed, and ENERGY STAR certificate awarded, as shown in Figure 1.1. The label is proudly placed on circuit breaker box.

Figure 1.1 New Home ENERGY STAR Label

Beyond the ENERGY STAR Certification, a residence may become a Zero Energy Ready Home (ZERH). The U.S. Department of Energy (DOE) Zero Energy Ready Home is a distinction that verifies the energy consumption of a home equals the energy generated from renewable sources at the home. The U.S. Department of Energy publication of National Program Requirements mandates the specific design requirements that must be field tested, verified, and approved for this prestigious qualification [23]. Requirements include home features involving insulation, ducting, water system heating and delivery, lighting and appliances, indoor air quality, and renewable energy generation. According to the Zero Energy Project, taxpayers and builders may receive up to 30% of the cost of photovoltaic systems and solar hot water systems through the Residential Renewable Energy Tax Credit. Additionally, the Residential Energy Efficiency Tax Credit targets existing homes that perform energy efficient equipment upgrades in the value of up to $500 [24].

Additionally, a residence may earn the label of a Renewable Energy Ready Home (RERH). To become a RERH, specifications published by the U.S. Environmental Protection Agency focus on solar energy systems. The Site Assessment Tool allows builders and homeowners to input information about the home and determine whether the site is a good candidate for solar array performance as compared to maximum [25]. Sites that can achieve up to 75% of maximum generation are flagged as a promising location. New York City's Department of Design and Construction offers an online geographical assessment tool to determine viable locations for geothermal heating and cooling system development [26].

1.6.3 Additional Tax Credits

1.6.3.1 Renewable Energy

Installation of geothermal heat pumps, small wind turbines, solar energy systems, and fuel cells are eligible for tax credits to help the homeowner recover costs. The offer does not expire until December 31, 2021, existing homes and new construction are eligible, and both primary and secondary residences qualify. The tax credit dollar amount is graduated based upon the year the system is installed, as summarized in Table 1.3.

Table 1.3 Renewable Energy Tax Credit Percentage

Calendar Year Installed	Tax Credit
2018 and 2019	30% of system cost
2020	26% of system cost
2021	22% of system cost

Data from DSIRE® current as of March 14, 2020. www.dsireuse.org

Taxes the Tax Magazine SALT (State and Local Taxes) Block reported in 2016 that several states including Florida, Arizona, and Rhode Island offer property tax valuation modifications for residences using geothermal energy systems [6]. Property tax exemptions in Montana and North Dakota are available for homes using alternative energy systems to fossil fuel. The publication was clear in stating that the property tax valuation and exemption incentives varies throughout the

United States by renewably energy source, duration of incentive, and value of incentive. Thus, each potential site for renewable system implementation must be considered separately. This variability is considered further in CHAPTER III.

1.6.3.2 Qualified Energy Improvements

Improving the home through insulation, new metal or asphalt roofing, windows, doors, and skylights with efficiency rating approved by ENERGY STAR can result in tax credits. The amount of the tax credit is 10% of the cost of the materials only and cannot exceed $500. Credits are filed with annual taxes and must include receipts and a Manufacturer's Certification Statement that the product complies with the requirements for tax credit eligibility.

1.6.4 EPA Geothermal-Specific Energy Incentive Programs

According to the Database of State Incentives and Renewables (DSIRE®), the only personal tax credit program that applies to all states for geothermal technology is the Residential Renewable Energy Tax Credit. This incentive program offers the most robust financial benefit. Others investigated below are either state specific or loan programs.

1.6.4.1 Residential Renewable Energy Tax Credit

The Residential Renewable Energy Tax Credit offers up to 30% financial incentive in the form of a tax credit for geothermal heat pump systems placed in new or existing homes [27]. The residences do not have to be the primary dwelling. The credit gradually steps down from 30% to 22% based up the year of installation from 2019 to 2022.

1.6.4.2 FHA PowerSaver Loan Program

Federal Housing Administration (FHA) offers the PowerSaver loan for eligible homeowners to make energy improvements to their homes [28]. Minimum credit score and debtto-income ratio requirements must be met, and the program applies to principle residences only. Maximum loan amount is $7,500 for a maximum payback period of twenty (20) years. Interest rates vary by customer from 4.99% to 7.75%.

1.7 Conclusion

Significant research and data collection exist for geothermal heat pump systems. The scope of the data includes design, construction, location feasibility, policy history, barriers and suggestions for the future. Several themes emerge: significant energy savings compared to traditional energy systems, goals of districts, states, or countries to achieve a renewable system percentage threshold in coming years, high initial installation cost due to drilling and borefield construction, and a long history of financial incentives to promote growth. Much of the existing studies focus on district heating systems rather than individual residences. For the data on individual residences, gaps occur in using actual heating and cooling load data from a specific home in the climate of interest, rather than from database or square foot models. Pairing the building load with location-specific soil properties for designing the GHE, as well as including all local and federal financial incentives will result in a more accurate payoff period calculation. Marrying these three site-specific parameters will result in the most accurate payoff period calculation. Individual homeowners in a specific geographical location can make the most educated decision on whether to adopt a residential geothermal energy system.

CHAPTER II

TECHNO-ECOMONIC ANALYSIS OF GEOTHERMAL SYSTEM IN RESIDENTIAL BUILDING IN MEMPHIS, TENNESSEE

The residential sector in the United States relies prolifically on electric cooling and natural gas heating, ventilating, and air conditioning systems. Technology advancement for more energy efficient and cost-effective energy systems is continuous, and a geothermal energy system is an attractive alternative to electricity and natural gas. This study investigates a simulated residential building in Memphis, Tennessee (TN) to assess the energy savings by replacing the existing electric/gas system with a geothermal heat pump system. Further, economics are considered to examine the payoff period and ultimate viability for geothermal technology in this region. EnergyPlus™, the U.S. Department of Energy (DOE) whole building simulation engine, analyzed a prototype home in Memphis, TN with this common utility system. City-specific ground characteristics are used to customize the ground heat exchanger and optimize result accuracy. Simulations reveal that replacing the existing system with a geothermal system accomplishes a 26% reduction in energy use. Our results prove an exciting alternative for homes in Memphis, TN to achieve abundant energy savings. Despite lower meter readings, a homeowner must consider initial capital investment and payoff period. This study provides city-customized payoff data by using local ground characteristics for design, location-specific home features, and regional plus federal incentive programs. Methods used within create a unique and accurate template procedure for identifying promising regions for residential geothermal systems throughout the broader United States.

2.1 Introduction

Residential homeowners shouldering the burden of high utility costs are seeking more affordable alternatives to existing home operations. A major contributor to the monthly utility bill is the residence's heating, ventilation, and air conditioning (HVAC) system. According to the U.S. DOE, HVAC costs average 48% of the energy consumption of a traditional home in the United States [29]. In comparison to other cities in the country, Memphis, TN consistently ranks among the lowest average utility bills in the residential sector [30]. The data supporting this ranking information was retrieved from a 2019 survey by Memphis Light, Gas and Water (MLGW), the city's utility provider. MLGW purchases power from, and is the largest customer of, the Tennessee Valley Authority (TVA). Since 2010 Memphis has ranked in the top 4 of 41 cities for lowest average winter utility bill, assuming a standardized usage amount. Competing cities were of equivalent size within the same or adjacent climate zones. This high rank is due to the low utility costs. For the overall annual utility bill average, Memphis, TN ranked 13 of 41 cities of similar climate conditions.

Despite competitive rates, modifications to existing systems would be even more attractive to homeowners nationwide if the alternative energy source produced monthly cost reductions. Prior research indicated the massive opportunities for energy savings and cost savings by replacing traditional HVAC systems with ground source heat pumps (GSHP). Liu et al. [1] stated that 98% of space heating (SC) in the residential sector used electricity as the energy source. The contribution of electricity rose to 100% within the single-family subsector of residential dwellings.

Simulation results predicted national savings of 4.3 quadrillion Btu and $38.2 billion annually if GSHP technology replaced electric.

Geothermal technology experiences slow adoption despite the attraction of an alternate energy source for the home and monthly cost reduction. Abundant research on residential ground source heat pump (GSHP) systems claims high initial cost is the main barrier for widespread adoption in both commercial and residential sectors [31][2][3][4][5][6]. Despite tax rebates, incentives, loan programs, and future energy savings, the initial high cost of ground heat exchangers (GHE), drilling, and other equipment is too high for many homeowners. These blockades are an international concern.

Domestically, federal and state financial incentive programs attempt to reduce the initial investment, along with other creative means under investigation. Goetzler et al. [32] cite a utility on-board financing initiative that grants a low or no interest loan for the installation. As the bills are received monthly, the loan balance is reduced by the amount of savings on that utility bill. Therefore, financing the geothermal system is hidden by the unchanging out-of-pocket expenses by the homeowner, until the loan is paid in full. Sonnier [6] reported property tax exemptions in Montana and North Dakota for the capital investment of geothermal heat pump systems in single or multi-family residences. These exemptions, however, were limited by duration and maximum dollars. Lim [14] performed a simple payback analysis of ground source heat pump (GSHP) systems in United States residences. His findings on high initial cost and long payback periods are concluded by stating increased accuracy with better energy use calculation methods. Heating and cooling loads will be more accurate with use of EnergyPlus™ [33] by the U.S DOE. Ground loop parameters will be more accurate by considering regional soil characteristics. Payback period will be more accurate if regional, state and federal incentive programs are considered cumulatively. All of these improvements suggested by Lim were implemented in this study for the Memphis, TN baseline home. Paralleling the commerial photovoltaic incentive analysis by Zhang et al. [34], this study performed the residential geothermal incentive analysis.

Using the heat available underground may provide the solution to high energy costs resulting from heat generation. The scope of this investigation is a residential building in Memphis, TN. A common electric air conditioning cooling system and natural gas furnace heating is replaced with a high-efficiency heat pump and ground heat exchanger. Methods of investigation include calculations of required borehole length as presented by Philippe et al. [35], where vertical geothermal borefield design process is shown in detail. The simulation engine employed is the EnergyPlus™, a whole building energy analysis tool by the U.S. Department of Energy. Justification of the EnergyPlus tool for analysis of residential buildings presented by Cho and Mirianhosseinabadi [36] proves its validity. Reference files and additional studies by Kang and Cho [36] provided useful guidance on ground source heat pump modeling.

Along with the surge in GSHP technology, both in the commercial and residential sector, many improvements have been designed and tested to improve the performance of GSHP. With improved performance and efficiency, and potential installation cost saving methods, the payback period may decrease enough to attract more individuals and institutions to adopt the energy source. Spitler [12] reports on several cost saving improvements, including both system components and construction methods. On the system component side, one major improvement is improved thermal conductivity of the grout surrounding the U-tube, as compared with traditional bentonite grout. Thermally enhanced high density polyethleye (HDPE) pipe, along with corrugated pipe features to increase surface area for heat transfer, can also improve efficiency and energy savings.

For programming and savings, [12] emphasized shutting off the ground loop fluid circulating pump when the heat pump was not required.

Gaps exist in the published analysis of the energy savings and financial implications of geothermal residential HVAC. Lim [5] concluded that there are 3 improvements to their research that would yield more accurate payoff analyses. First, they recommend improving heating and cooling loads estimation methods. Their research time used data from the Residential Energy Consumption Survey (RECS) to group residences by climate region and state. [5] stated that better energy use inputs would result from EnergyPlus™ or a comparable simulation engine. Second, heat pumps were sized based upon this database energy use data. In this chapter, specific building characteristics were considered such as year built, insulation type, fenestration type, construction envelope, number of occupants, and site-specific weather patterns. Third, only federal tax credits and rebates were considered, due to lack of knowledge of the state and regional programs. This chapter encompasses all known incentives, federal and local.

This study analyzed the energy consumption of a vertical ground heat exchanger and compared the consumption to an electric air conditioning/gas furnace system. The prototype home is a suburban residence in Memphis, TN. The subject property is studied as a retrofit application. In order to make the simulation more customized, a simulation template is created allowing inputs for local soil properties, actual heating and cooling load magnitudes, resulting in borefield parameter calculations. With this template, other locations can be evaluated following the same model. Here, the first objective is to analyze the change in energy consumption with the installation of the high efficiency water-to-air heat pump with ground heat exchanger. The consumption savings will then be aligned with the capital investment, utility cost data, and ultimate payback period to reveal the home's viability for a geothermal system implementation. Presentation of the whole life cycle cost is revealed for this alternate HVAC system.

2.2 Building Description of Suburban Residence

The prototype model is a residential building located in Memphis, TN. The home resides at elevation *265 ft* above sea level and is in the suburbs terrain classification. The conditioned building living area is *2401* ft^2. Construction features include an unconditioned crawlspace and attic. The existing heating system uses 100% natural gas and has a design nominal capacity of *22.2 kBtu/hr*. The existing cooling system uses 100% electricity. For the cooling system, the design cooling capacity is *2.03* tons, coefficient of performance (COP) of 3.97. Heating and cooling fan air flow rate is *825 CFM*. The prototype home is shown in Figure 2.1, retrieved from the DOE Residential Prototype Building Models [37].

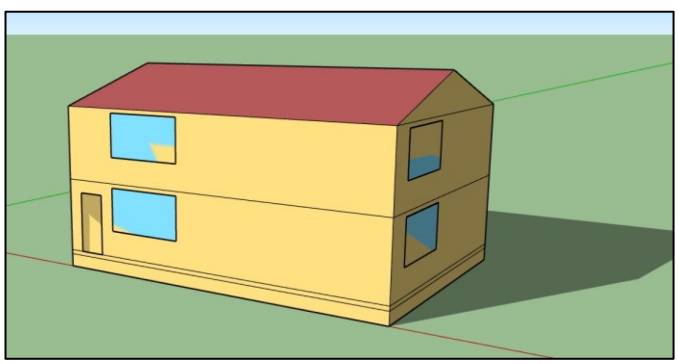


Figure 2.1 Case Study Residence, Gas Furnace/Crawlspace, Memphis, TN

Prototype home graphic from Trimble SketchUp 2018 3D Design Software.

A comparison was completed to validate the energy use intensity (EUI) of the baseline prototype model through EnergyPlus™ with the published data in the U.S. DOE's Building

Performance Database (BPD) [38]. Filters included single-family, detached residences in Climate Zone 3A (warm, humid) where Memphis, TN is located. As Figure 2.2 displays, the highest percentage of homes reveal an EUI value of 62 kBtu/ft^2/year and median value of 91 kBtu/ft^2/year.

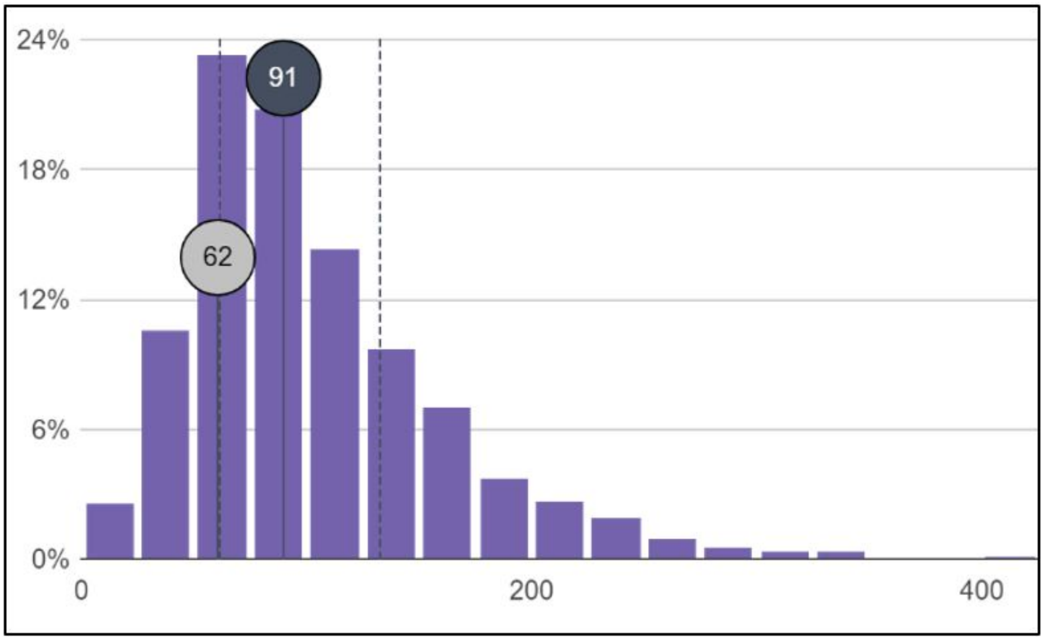


Figure 2.2 Histogram of Published EUI Values for Residential Buildings in Climate Zone 3A [38]

The EUI determined through the EnergyPlus™ simulation of the baseline model revealed a source energy use intensity value of 77. The simulated value does fall within the expected range as published through the BPD. The alternate geothermal energy source system modeled within drops the EUI value for this prototype model to 67, representing an improved energy use system.

2.3 Geothermal System Analysis

2.3.1 Geothermal Heat Pump System Description

The geothermal heat pump system is represented by the schematic in Figure 2.3. The demand side is a single zone living unit, and the source side is the ground heat exchanger. The heat pump integrates the source side (ground) and the demand side (zone). The source side and demand side intersect at the water to air heat pump, operating in one direction during the heating season and in reverse during the cooling season.

2.3.1.1 Heating Mode

In the cold months, the ground source heat pump operates in heating mode. In heating mode, the source side provides heat from the ground to deliver to the water source heat pump by absorption by the water in the ground heat exchanger. Within the heat pump, the refrigerant coil interacts with the demand side, or zone, through an air handling unit (AHU) and interacts with the source side at the condenser. The refrigerant absorbs heat from the ground water through the condenser, is superheated by the compressor, then runs through the AHU where a fan will blow the cooler zone air over the hot refrigerant coil. It is through the AHU that outside air (OA), return air (RA), and exhaust air are maintained at design requirements. Depending on the outside air temperature, a supplemental heating coil often augments the heat available from the heat pump. The refrigerant transfers heat to the cool air, thus heating the air and delivering it to the zone. The refrigerant exiting the zone is further cooled by drop in pressure by an expansion valve, then travels back to the condenser to receive heat from the ground water. This begins the process all over again. For the prototype home in Memphis, TN, the heating months are October through April. Days in May vary, sometimes requiring heating, sometimes cooling, or neither, depending on the homeowner's comfort preferences. The heating temperature setpoint for the EnergyPlus™ simulation is an inside air temperature of 75°F. If the thermostat falls below this setpoint, the heating system will activate.

2.3.1.2 Cooling Mode

In warm months, the ground source heat pump operates in cooling mode. In cooling mode, the source side acts as a heat sink that will receive heat absorbed from the water source heat pump. Same as in heating mode, within the heat pump, the refrigerant coil interacts with the demand side, or zone, through an AHU and interacts with the source side at the condenser. However, the system operates in reverse in cooling mode. The refrigerant rejects heat to the ground water through the condenser, is further cooled by drop in pressure by an expansion valve, then runs through the AHU where a fan will blow the warmer zone air over the cool refrigerant coil. The refrigerant absorbs heat from the warm air, thus cooling the air and delivering it to the zone. The hot refrigerant exiting the zone is superheated by the compressor, then travels back to the condenser to reject heat to the ground water, thus cooling the refrigerant. This begins the process all over again. For the prototype home in Memphis, TN, the cooling months are June through September. May and September vary, sometimes requiring cooling, sometimes heating, or neither, depending on the homeowner's comfort preferences. The cooling temperature setpoint for the EnergyPlus™ simulation is an inside air temperature of 75°F. If the thermostat rises above this setpoint, the cooling system will activate.

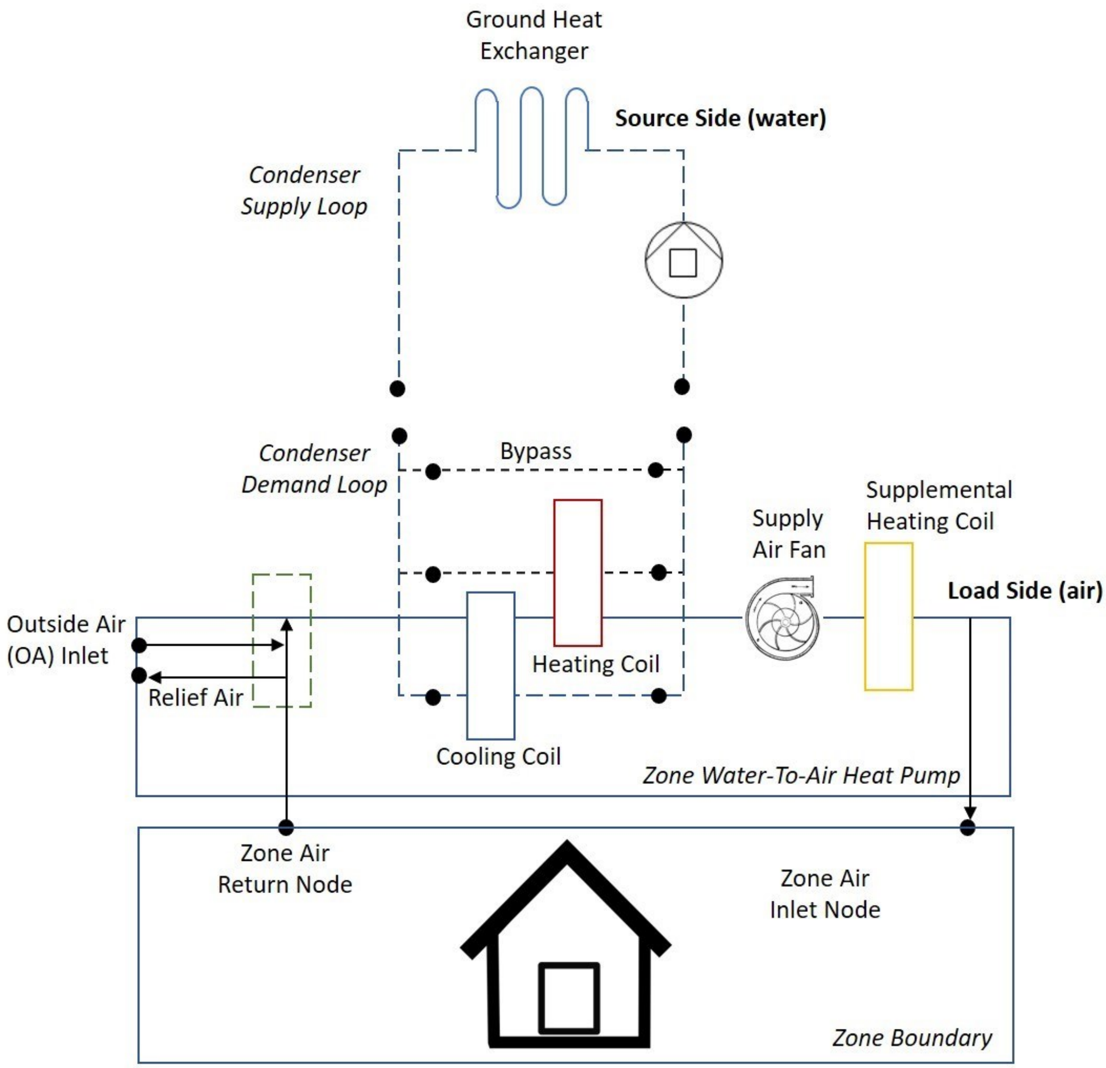


Figure 2.3 Geothermal Heat Pump System Schematic [39]

2.3.2 Building Model Analysis Materials and Methods

Using the heat available underground may provide the solution to high energy costs resulting from heat generation. The scope of this investigation is a residential building in Memphis, TN. A common electric air conditioning cooling system and natural gas furnace heating is replaced with a high-efficiency heat pump and ground heat exchanger. Materials and methods of investigation were executed in a logical sequence, with a series of inputs and outputs throughout.

Calculations of required borehole length as presented by Philippe et al. [35], where vertical geothermal borefield design process is shown in detail and outlined in this chapter. The simulation engine employed is the EnergyPlus™, a whole building energy analysis tool by the U.S. Department of Energy. Reference files and additional studies by Kang and Cho [40] provide useful guidance on ground source heat pump modeling. Table 2.1 outlines the chronology of steps employed for this study. The steps highlight the major action items and do not highlight intermediate components critical to the major action items.

Table 2.1 Chronological Steps in Analysis Employed in This Study

STEP	METHOD
1	Collect prototype home and weather data
2	Simulate energy use of baseline electric/gas heating and cooling system
3	Gather local soil characteristics such as porosity, classification type, and diffusivity
4	Calculate required vertical borehole length to accommodate heating and cooling loads
5	Retrofit prototype EnergyPlus™ home with geothermal heat pump system
6	Simulate retrofit prototype home with geothermal system, using inputs from previous steps
7	Gather energy use information for geothermal system and compare to baseline system
8	Calculate annual savings based upon local utility rates
9	Evaluate capital investment and annual savings to calculate payback period
10	Conclude whether payback period is acceptable or unacceptable to consumers
11	Determine required financial assistance package to achieve a consumer accepted payback period

EnergyPlus™ platform performed the computer-aided annual simulation, along with spreadsheet calculators provided by EnergyPlus™ to generate heat pump coefficient input data.

The input coefficients are generated by the manufacturer's heat pump performance curves. With the performance characteristics at multiple input parameters, the coefficients are calculated without heat transfer equations. Entering water temperature, water flow rate, entering air temperature, cooling or heating capacity, power input, and energy efficiency ratio at up to 7 data points generates the equation coefficients for a particular heat pump. These input coefficients are required for use of the Water-to-Air Heat Pump Equation Fit model in the software. The high-efficiency heat pump used in this model is the Bosch Greensource™ SM Series Residential Geothermal Heat Pump SM036 [41]. The EnergyPlus™ simulation of this prototype home determined the values of q_y, q_m and q_h. These values are the yearly, monthly, and hourly ground heat loads, respectively, that will later be inputs for designing the total ground borehole length.

The United States Department of Agriculture Natural Resources Conservation Service provides interactive soil survey across the United States [42]. For the Memphis, TN metropolitan area, the predominant soil type identified is silt loam. Interactive map of the Memphis area is shown in Figure 2.4, identifying the analysis region for soil composition. By identifying an Area of Interest (AOI) through the interactive tool, a soil map tool reveals the predominant soil type. The soil map quantifies the number of acres within the AOI that are classified as each soil type.

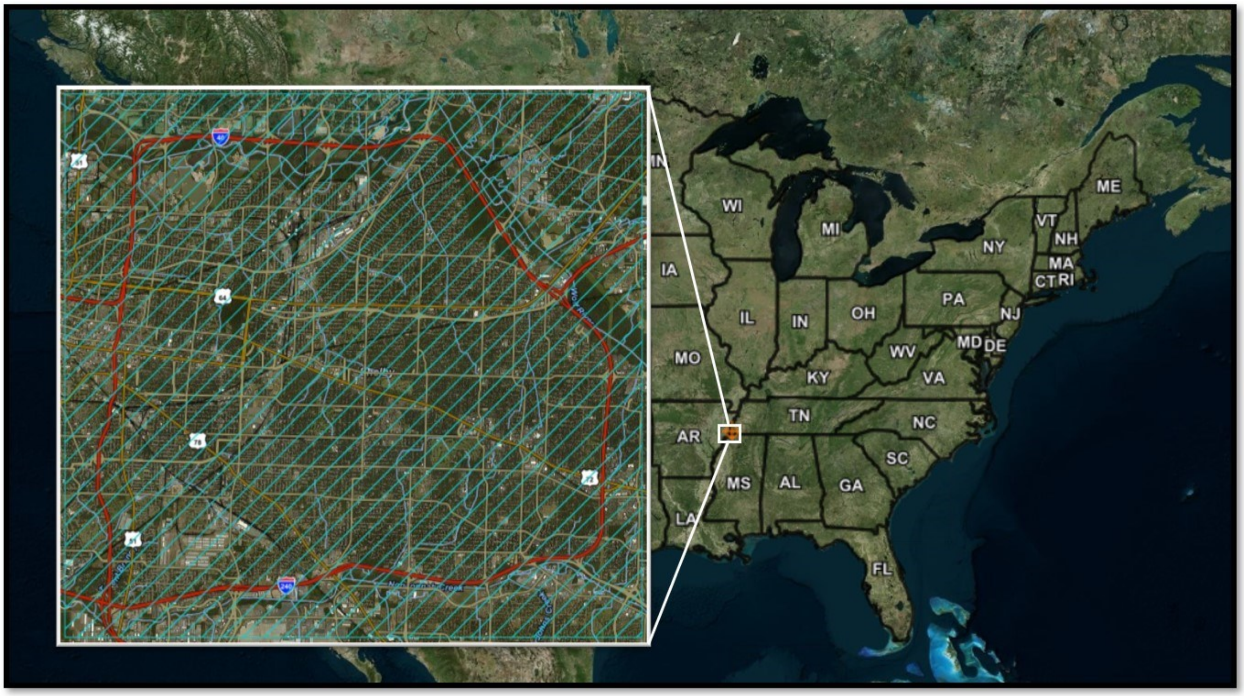


Figure 2.4 Memphis Metropolitan Area of Interest (AOI) for Soils

Graphic created by overlaying the zoomed in AOI from the Web Soil Survey onto a map of the United States. United States Department of Agriculture (USDA), "Web Soil Survey." [Online]. Available: https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx. [Accessed: 25-Feb-2020].

This case study employs the sizing calculations presented by Philippe et al. [35] for a vertical geothermal borefield. Using the soil properties and facility loads, determination of the required borehole length is given by Equation 2.1:

$$L = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_h R_{6h}}{T_m - (T_g + T_p)} \tag{2.1}$$

where

q_y is the yearly average ground heat load [W]

q_m is the highest monthly ground heat load [W]

q_h is the peak hourly ground load [W]

R_b is the effective borehole thermal resistance [m-K/W]

R_{10y} is the effective ground thermal resistance corresponding to 10 years [m-K/W]

R_{1m} is the effective ground thermal resistance corresponding to 1 month [m-K/W]

R_{6h} is the effective ground thermal resistance corresponding to 6 hours [m-K/W]

T_m is the mean fluid temperature in borehole [°C]

T_g is the undisturbed ground temperature [°C]

T_p is the temperature penalty for multiple boreholes [°C]

The values of q_y, q_m, and q_h are extracted from EnergyPlus™ simulation of the original case study prototype home's annual energy consumption. Data was analyzed for yearly, monthly, and hourly heating and cooling loads, respectively. Effective ground thermal resistances corresponding to 10 years, 1 month, and 6 hours are determined by Equation 2.2 through Equation 2.4:

$$R_{10y} = \frac{1}{k} f_{10y}(\alpha, r_{bore}) \tag{2.2}$$

$$R_{1m} = \frac{1}{k} f_{1m}(\alpha, r_{bore}) \tag{2.3}$$

$$R_{6h} = \frac{1}{k} f_{6h}(\alpha, r_{bore}) \tag{2.4}$$

The correlation function in Equation 2.5 uses the ground thermal diffusivity, α, and borehole radius to determine ground thermal resistances over the desired time durations. The correlation factors are shown in Table 2.2. Thermal diffusivity of silt loam soil is 0.042760 m^2/day as published by the International Ground Source Heat Pump Association [43].

$$f = a_0 + a_1 r_{bore} + a_2 r^2{}_{bore} + a_3 \propto + a_4 \propto^2 + a_5 ln(\propto) + a_6 ln(\propto)^2 + a_7 r_{bore} \propto + a_8 r_{bore} ln(\propto) + a_9 \propto ln(\propto) \tag{2.5}$$

Table 2.2 Correlation Factors for f_{10y}, f_{6m}, f_{1h} [42]

	f_{6h}	f_{1m}	f_{10y}
a_0	0.6619352	0.4132728	0.3057646
a_1	-4.815693	0.2912981	0.08987446
a_2	15.03571	0.07589286	-0.09151786
a_3	-0.09879421	0.1563978	-0.03872451
a_4	0.02917889	-0.2289355	0.1690853
a_5	0.1138498	-0.004927554	-0.02881681
a_6	0.005610933	-0.002694979	-0.002886584
a_7	0.7796329	-0.6380360	-0.1723169
a_8	-0.3243880	0.2950815	0.03112034
a_9	-0.01824101	0.1493320	-0.1188438

Undisturbed ground temperature, T_g, values published by Virginia Tech [44] reveal 62°F [16.67°C] in Memphis, TN. Nationwide temperature data is shown in Figure 2.5.

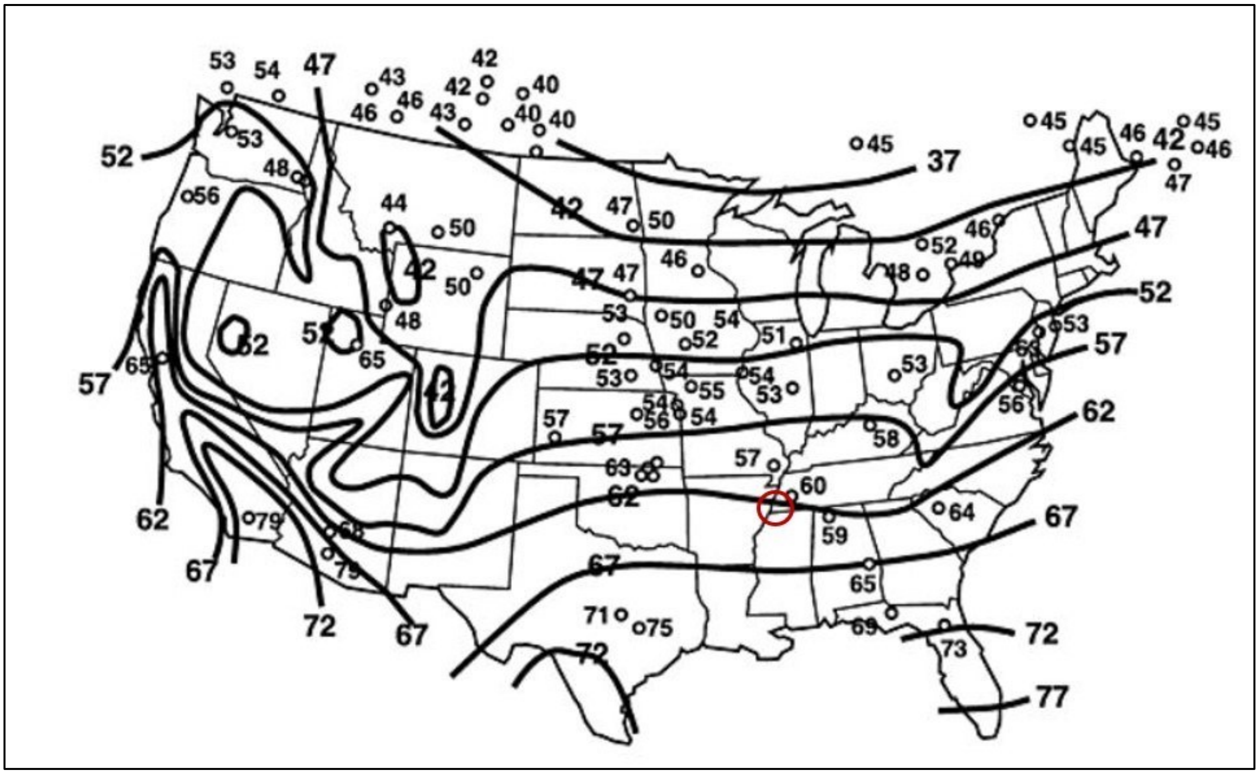


Figure 2.5 Contiguous United States Mean Annual Earth Temperature Map [44]

In a publication in the Journal or Hydrometeorology [45], a simple model of determining soil conductivity is given by:

$$k = \left[\frac{1.5(1-\theta_s) + 1.3\theta_s S_r}{0.75 + 0.65\theta_s - 0.4\theta_s S_r}\right](0.4186) \tag{2.6}$$

Where k is soil conductivity in [W/m-K], θ soil volumetric water content in [in/in], θ_s is the saturated porosity in [in/in], and $S_r = \frac{\theta}{\theta_s}$. The value of θ is location specific and determined from the Web Soil Survey provided by the USDA Natural Resources Conservation Service [42]. It was studied and published for all regions of Tennessee by the University of Tennessee

Agricultural Experiment Station [46]. Published values for the Memphis area vary based upon soil depth, slight variations in soil texture, and the lab sample series. A value of θ = 0.271 is used for this study because it occurs at a depth greater than 40 inches in silt loam, and is a respectable midrange value for the soil sample series.

The value θ_s for various common soil types is published by [45], as shown in Table 2.3.

Table 2.3 Saturated Porosity by Soil Texture

Soil. No.	**Texture**	**Sand (%)**	**Silt (%)**	**Clay (%)**	θ_s
1	Sand	94	1	5	0.405
2	Sand	93	1	6	0.432
3	Sandy loam	67	21	12	0.419
4	Loam	40	49	11	0.456
5	Silt loam	27	51	22	0.483
6	Silt loam	11	70	19	0.479
7	Silty clay loam	19	54	27	0.491
8	Silty clay loam	8	60	32	0.507
9	Clay loam	32	38	30	0.522
10	Silt loam	2	73	25	0.554
11	Loam	50	41	9	0.489
12	Sand	92	7	1	0.415

B. Tong, "An Empirical Model for Estimating Soil Thermal Conductivity from Soil Water Content and Porosity," *J. Hydrometeorol.*, vol. 17, p. 602, 2016.

Effective borehole thermal resistance, R_b, given by Equation 2.7 assumes inner pipe radius 0.0137 m, outer pipe radius 0.0167 m, U-tube distance 0.0511 m, and grout thermal conductivity 2.07 W/m-K as published by [12] for thermally enhanced bentonite grout. Ground thermal conductivity, *k*, is determined from Equation 2.7 as previously explained.

$$R_b = R_g + \frac{R_p + R_{conv}}{2} \tag{2.7}$$

$$R_p = \frac{\ln\left(\frac{r_{pipe,ext}}{r_{pipe,in}}\right)}{2\pi k_{pipe}} \tag{2.8}$$

$$R_g = \frac{1}{4\pi k_{grout}}\left[ln\left(\frac{r_{bore}}{r_{pipe,ext}}\right) + ln\left(\frac{r_{bore}}{L_U}\right) + \left(\frac{k_{grout} - k}{k_{grout} + k}\right) ln\left(\frac{r^4{}_{bore}}{r^4{}_{bore} - \left(\frac{L_U}{2}\right)^4}\right)\right] \tag{2.9}$$

$$R_{conv} = \frac{1}{2\pi r_{pipe,in} h_{conv}} \tag{2.10}$$

where

k is the ground thermal conductivity [W/m-K].

α is the ground thermal diffusivity [m^2/day].

r_{bore} is the borehole radius [m].

f is the correlation function.

k_{grout} is the thermal conductivity of the grout [W/m-K].

$r_{pipe,ext}$ is the outside radius of the pipe [m].

$r_{pipe,in}$ is the inside radius of the pipe [m].

L_U is the center-to-center distance between the pipes [m].

h_{conv} is the convective film coefficient [W/m^2-K].

The simulation laminar flow where h_{conv} = 100 W/m^2-K [17.6 Btu/hr-ft^2-°F]. Using Equations 2.2 through 2.10, all data was calculated for inputs to Equation 2.1. The resulting borehole depth for a single, vertical ground heat exchanger pipe is L = 301 m. This result is specific to the Memphis, TN case study prototype home heating and cooling loads, soil properties, and local weather data.

Additional soil property used in reference for EnergyPlus™ input parameters is soil density, ρ, from Structural Engineering Resources [47]. Silt loam density 1380 kg/m^3 is displayed in Table 2.4.

Table 2.4 Density of Different Soil Types

Soil Type	ρ [kg/m^3]
Sand	1430
Loamy sand	1430
Sandy loam	1460
Loam	1430
Silty loam	1380
Silt	1380
Sandy clayey loam	1500
Clayey loam	1390
Silty clayey loam	1300
Silty clay	1260
Sandy clay	1470
Clay	1330

StructX, "Density Ranges for Different Soil Types." [Online]. Available: http://structx.com/Soil_Properties_002.html. [Accessed: 25-Feb-2020].

The value of ground specific heat capacity, c_p, is determined by Equation 2.11 using the silt loam density, ground thermal conductivity from Equation 2.6, and ground thermal diffusivity, α:

$$c_p = \frac{k}{\alpha\rho} \tag{2.11}$$

Spreadsheet calculations shown in Table 2.5 display the inputs to EnergyPlus™ as discussed through the previous equations and calculations.

Table 2.5 Case Study Prototype Home Input Calculations Spreadsheet

Calculations Spreadsheet Template – Memphis, TN Location Shown			
Set of Inputs			
Parameter	*Variable*	*Value*	*Units*
Heat Pump Characteristics [41]			
Nominal Capacity	*Cap*	10.55	kW
Heating Coefficient of Performance	COP_H	4.4	[-]
Cooling Coefficient of Performance	COP_C	6.153	[-]
Ground Loads			
Peak Hourly Ground Load	q_h	6970	W
Monthly Ground Load	q_m	1922	W
Yearly Average Ground Heat Load	q_y	267	W
Parameters needed to Calculate k			
Volumetric Water Content	θ	0.271	m/m
Porosity	θ_s	0.483	m/m
Ration of θ to θ_s	S_r	0.5611	[-]
Parameters needed to Calculate R_{6h}, R_{1m}, and R_{10y}			
Correlation Factor for R_{6h}	f_{6h}	0.1856399	[-]
Correlation Factor for R_{1m}	f_{1m}	0.3484745	[-]
Correlation Factor for R_{10y}	f_{10y}	0.3813252	[-]
Ground Properties			
Ground Thermal Conductivity	k	0.49406	W/m-K
Ground Thermal Diffusivity	α	0.042760	m^2/day
Ground Specific Heat Capacity	c_p	998283.62	J/kg-K
Undisturbed Ground Temperature	T_g	16.67	°C
Fluid Properties			
Thermal Heat Capacity	c_p	4200	J/kg-K

Table 2.5 (continued)

Total Mass Flow Rate / kW of Peak Hourly Ground Load	m_{fls}	**0.05**	**kg/s-kW**
Max/Min Heat Pump Inlet Temperature	$T_{in,HP}$	37.1	°C
Borehole Characteristics			
Borehole Radius	r_{bore}	0.0600	m
Pipe Inner Radius	$r_{pipe,in}$	0.0137	m
Pipe Outer Radius	$r_{pipe,ext}$	0.0167	m
Grout Thermal Conductivity	k_{grout}	2.07	W/m-K
Pipe Thermal Conductivity	k_{pipe}	0.38	W/m-K
U-Tube Distance	L_U	0.0511	m
Convective Film Coefficient	h_{conv}	1000	W/m^2-K
Set of Results			
Parameter	*Variable*	*Value*	*Units*
Calculation of Effective Borehole Thermal Resistance			
Convective Resistance Inside Each Tube	R_{conv}	0.011617	m-K/W
Pipe Resistance	R_p	0.082933	m-K/W
Grout Resistance	R_g	0.056129	m-K/W
Effective Borehole Thermal Resistance	R_b	0.103404	m-K/W
Calculation of Effective Ground Thermal Resistance			
Effective Ground Thermal Resistance Correlating to 6h	R_{6h}	0.3757451	m-K/W
Effective Ground Thermal Resistance Correlating to 1m	R_{1m}	0.7053312	m-K/W
Effective Ground Thermal Resistance Correlating to 10y	R_{10y}	0.7718228	m-K/W
Total Length Calculation Assuming No Borehole Thermal Interference			
Heat Pump Outlet Temperature	$T_{out,HP}$	28.8	°C
Average Temperature of Fluid in the Borehole	T_m	32.95	°C
Borehole Length	L	301.0	m

2.4 Incentive and Payback Analysis

2.4.1 Incentive Analysis

Once system performance data is calculated, payoff period for residential systems will drive the viability of execution. This payoff calculation depends on annual savings and federal and state monetary incentive programs. Annual savings in dollars per year relies on the electricity cost by state, shown in Table 2.6 below for a sampling of states, published by the U.S. Energy Information Administration [48].

Table 2.6 Electricity Prices by State Current December 2019 [48]

State	Cost [$/kWh]
Tennessee	0.1070
Maine	0.1680
Florida	0.1167
Minnesota	0.1372
Arizona	0.1326

United States Energy Information Administration, “Electricity Data Browser,” *October 2008*. [Online]. Available: https://www.eia.gov/electricity/data/browser/. [Accessed: 17-Feb-2019].

Federal and state financial incentive programs can drastically reduce the capital cost investment for various renewable energy home upgrades. Table 2.7 summarizes the applicable programs to this study in technology, sector, and program type presented by NC Clean Energy Technology Center’s DSIRE® database [49]. For comparison, several states’ incentives are displayed and the variety is clear in type and monetary value. Tax exemptions and rebates are as low as $100 in Minnesota and as high as $3,000 in Maine, both in addition to the Federal Residential Renewable Energy Tax Credit.

Table 2.7 Example of Incentive Programs by State [49]

	Program	Incentive
Federal Incentive	Residential Renewable Energy Tax Credit	Tax credit of 30% of investment
Tennessee	TVA Partner Utilities eScore Program	Geothermal Heat Pump: $250/Unit
Maine	Efficiency Maine Residential Home Energy Savings Program	Ultra-Low Greenhouse Gas Central Heating Systems: One third of the installation cost up to $3,000
Florida	Property Tax Abatement for Renewable Energy Property	100% property tax exemption
Minnesota	Minnesota Power Residential Energy Efficiency Rebate Program	Ground Source Heat Pump: $100-$200 per ton plus $200 for ECM motor
Arizona	Energy Equipment Property Tax Exemption	100% of increased value

NC Clean Energy Technology Center, "Programs (TN)," *DSIRE*, 1995. [Online]. Available: http://programs.dsireusa.org/system/program?fromSir=0&state=TN. [Accessed: 17-Feb-2020]

The Tennessee incentive programs are highlighted in this study. Results across the nation will vary drastically depending upon the annual energy savings by geographical location, as well as the state's incentive programs. Maine, Florida, Minnesota, and Arizona prototype home simulations, utility cost data, and incentives will determine the viability of ground source heat pump technology in their respective regions.

2.4.2 Payback Analysis

The second objective of this research is to determine the payback period for homes considering a transition to renewable ground source heat pump energy systems.

2.4.2.1 Simple Payback Period (SPP) [50]

A recent investigation on the viability of geothermal heat pumps in the Unites States is reported in [1]. The study revealed installation cost for residential geothermal systems within the range $3,000 - $5,000 per ton of cooling. That reported value of cost data is used within this study, however comparative cost data may be extracted from RSMeans® Mechanical Cost Data or through interviews with location-specific contractors. Key differences distinguish the study in [1] and this research. A different computer-aided simulation program ran simulations, a specific ground loop sizing procedure in was used [35], savings focused on the individual home savings rather than nationwide savings, all regional incentives were considered, and detailed payoff data was calculated. Further, itemizing costs into materials, ground loop cost per foot, and heat pump equipment will allow for greater cost customizing by geographical location. A commercial sector itemization is demonstrated by Kavanaugh et al. [4] provides a useful template for future study. Interviews with contractors within the regions of study will provide the most accurate construction cost data. For the 2401ft^2 prototype home in Memphis, TN, approximately a 4-ton capacity heat pump was used in the simulation. Using the midrange value of \$4,000, the installation will cost the homeowner \$16,000. This number will vary depending on parameters including, but not limited to borefield arrangement, equipment selected, and local retail prices. The value \$16,000 is used in this study to calculate a simple payback period for the prototype home, using Equation 2.12 and Equation 2.13 Defining in_1 as the 30% Residential Renewable Energy Tax Credit and in_2 as the \$250 TVA Partner Utilities eScore Program rebate, the initial net capital cost is calculated by:

$$SPP = \frac{Cost_{ca}}{AS} \tag{2.12}$$

where $Cost_{ca}$ is the initial capital cost [\$] after incentives, $Cost_{cb}$ is the capital cost before incentives, in_i, are incentives applied, and AS is annual savings [\$].

$$Cost_{ca} = (Cost_{cb}) - \sum in_i \quad (2.13)$$

2.4.2.2 Discounted Payback Period (DPP)

While the simple payback period (SPP) is the simplest method of calculating payback period, it does not account for the time value of money. Therefore, to more accurately perform a life-cycle cost analysis for the ground source heat pump system, a discounted payback period (DPP) analysis is also performed. This method accounts for discount rate and inflation.

The cost left to recover from the initial capital cost after incentives, $Cost_n$, is calculated using the discounted payback period given by Equation 2.14:

$$Cost_n = \frac{AS}{[(1+j)/(1+i)]^n} \quad (2.14)$$

where $Cost_n$ is the amount left to pay to recover initial investment (remaining deficit) at year n, i is the rate of inflation and j is the discount rate. From the Federal Energy Management Program's (FEMP) recent 2018 publication on discount rates, j = 3.0% for this study, and the rate of inflation is i = 2.44% [51]. However, in The Office of Management and Budget (OMB) Circular A-94, it is recommended to perform the payback analysis with the current year's real discount rate, as well as a real discount rate of 7% [52]. The publication states that the value of j = 7% represents the baseline average over the decades. Using both discount rates to calculate separate discounted payback periods demonstrates the extreme variability of the payback period calculation due to the discount rate employed [53]. Table 2.8 is a summary of parameters.

Table 2.8 Definition of Variables Used in Payback Analysis

Variable	Parameter	Units
$\boldsymbol{Cost_{cb}}$	Initial Cost Before Incentives	[$]
$\boldsymbol{in_i}$	Incentive *i* Savings	[$]
$\boldsymbol{Cost_{ca}}$	Initial Cost After Incentives	[$]
AS	Annual Savings	[$]
$\boldsymbol{Cost_e}$	Electricity Cost	[$/kWh]
j	Discount Rate	[%]
i	Inflation Rate	[%]
$\boldsymbol{Cost_n}$	Investment Deficit Remaining after Year *n*	[$]
SPP	Simple Payback Period	[years]
DPP	Discounted Payback Period	[years]

2.5 Results and Discussion

2.5.1 Energy Savings Analysis

The first objective of this research was to determine whether energy savings results from the replacement of original heating and cooling system in the case study prototype home with a ground source heat pump system. EnergyPlus™ simulation results revealed a total annual HVAC energy consumption reduction of 26%. This value represents the sum of electric and gas savings. The savings shown is for the total facility. Therefore, the savings percentage represents the savings on the monthly meter-based electric bill, not just the heating and cooling savings. For the average homeowner, the bottom line consumption savings is what matters, which is why the other components were not excluded from this meter total. Other components include interior lighting, exterior lighting, fans, pumps, and water systems. Monthly results are shown in Figure 2.6.

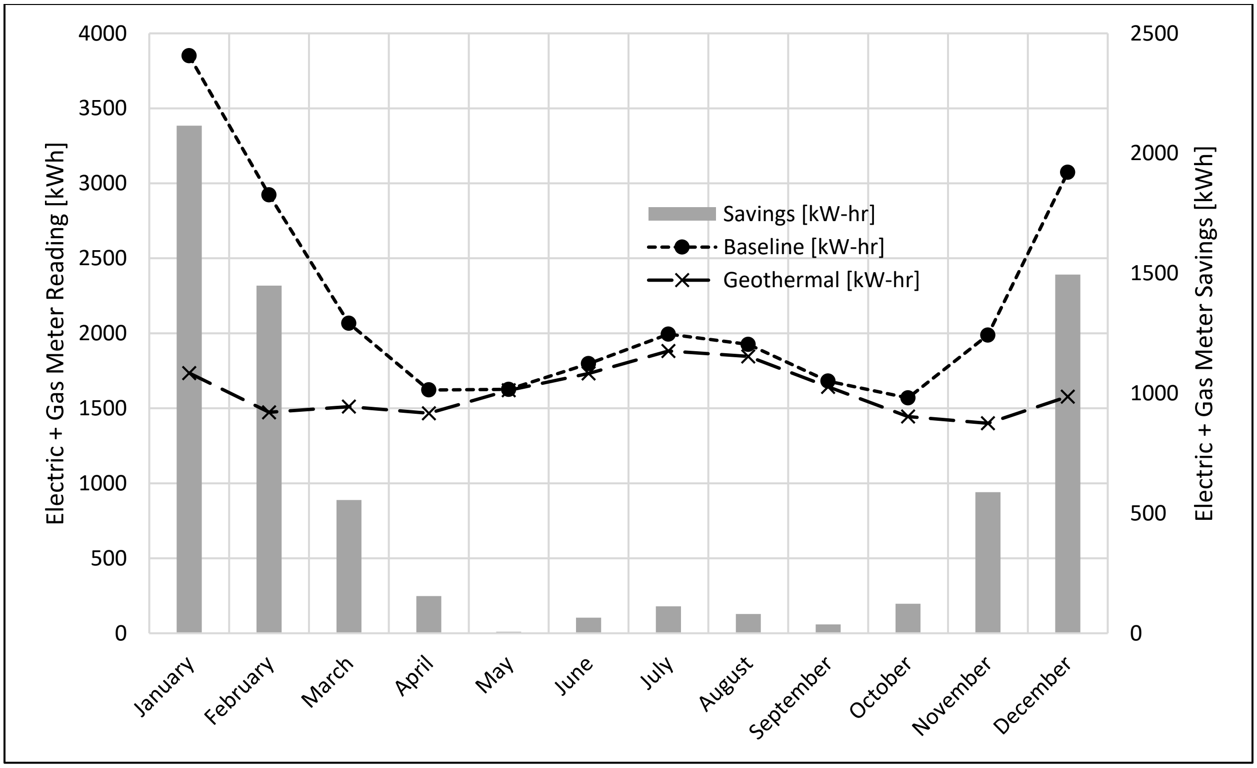


Figure 2.6 Site Energy Use Comparison Results

EnergyPlus™ uses a weather file representing a Typical Meteorological Year (TMY), so energy reduction will vary depending on actual weather conditions in the area. The case study prototype home also assumes occupancy of three people, differing from actual occupancy of many candidate homes for geothermal technology. As shown in Figure 2.6, the energy consumption is reduced every month of the simulation, ranging from the smallest savings of 6 kWh in May, to the largest of 2115 kWh in January.

Looking at the total annual use for a typical meteorological year in Figure 2.6, an overall energy consumption reduction of 26% is achieved when comparing the original electric cooling / gas furnace heating system to the retrofit geothermal cooling / heating system. To further explain the sources of the annual energy use changes as shown in the meter totals in Figure 2.6, a more detailed analysis of the source components is shown in Table 2.9. Note the total values in Figure 2.6 represent the total site energy and meter readings the homeowner is ultimately billed upon, but the values in Table 2.9 represent the itemized use by component.

Table 2.9 Whole Facility Site Energy Use Comparison

Component	Baseline System [kWh]	Geothermal System [kWh]	% Difference
Heating	7,581	1,022	-87%
Cooling	3,095	3,274	+6%
Fans	1,163	366	-69%
Pumps	0	390	Increase from Zero
Other Components[a]	14,293	14,292	0%

[a] Other components include interior and exterior lighting, interior equipment, and water heating systems

From the baseline HVAC system to the updated geothermal system, the most significant decrease in energy is from heating. As can be seen numerically in Table 2.9 and visually in Figure 2.7, the subject residence is clearly a heating-dominant building. Therefore, it can be predicted that savings will be significant in follow-on studies of residences in cold winter climates. Fans also result in decreased energy. Due to the ground water circulation, an increase from zero is seen in pumps. The results confirm a total source energy use reduction of 26%. Figure 2.7 depicts a graphical representation of the usage data.

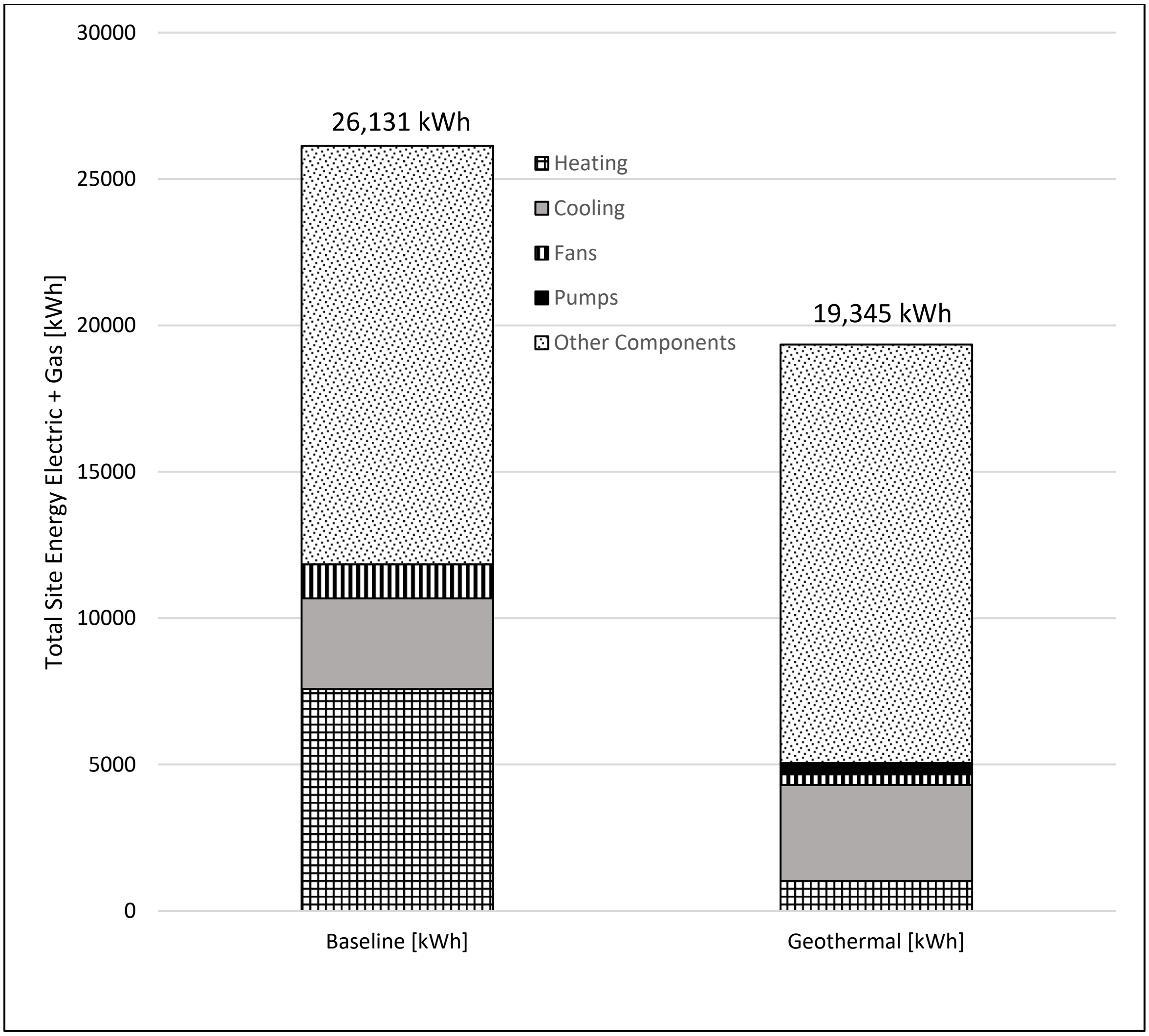


Figure 2.7 Site Energy End Use Comparison by Component

In the cooling mode, there is a slight increase in energy use. This increase may be justified by taking a closer look at the water temperatures exiting the GHE condenser. In Figure 2.8, an hourly record is investigated for August 5th through August 11th. These days were chosen because they exhibit some of the hottest days of the summer. Here, the outlet temperature from the GHE is graphed with the outdoor dry bulb air temperature. In the baseline electric cooling HVAC system, air is the fluid used to condense the hot refrigerant returning from the zone. Therefore, the outdoor dry bulb air temperature is the inlet temperature of the fluid (air) across the refrigerant coils. However, with the geothermal heat pump system, water is the fluid used to condense the hot refrigerant returning from the zone. Therefore, the outlet temperature of the GHE water is the inlet temperature of the fluid (water) across the refrigerant coils.

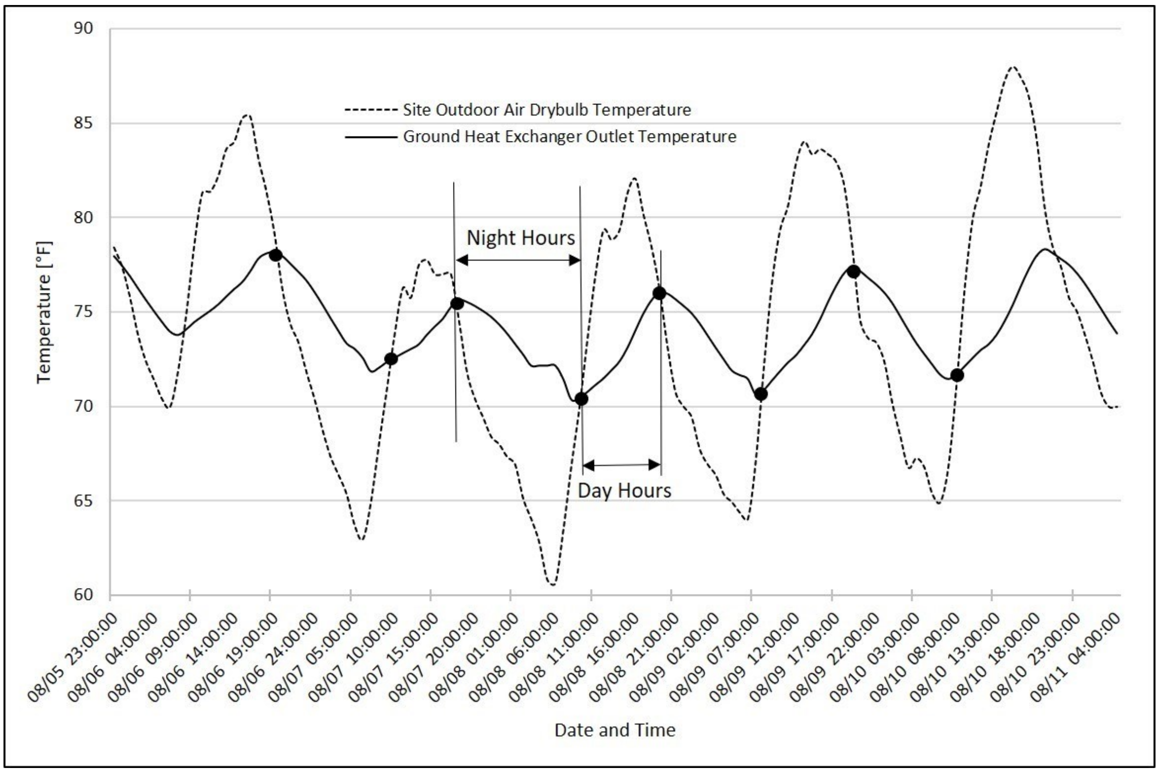


Figure 2.8 Inlet Temperature Comparison in Peak of Summer

Date range for peak of summer is August 5 – August 11.

As seen in Figure 2.8, during the hottest days of the year, the GHE outlet temperature can become hotter than the dry bulb air temperature. This occurs primarily during the night hours, as designated for one of the six days in Figure 2.8. The black dots represent the time at which the GHE outlet temperature drops below the dry bulb air temperature during the daytime or exceeds the dry bulb air temperature at nighttime. While Figure 2.8 only zooms in on a 6-day summer span on hot August nights, similar temperature differentials occur throughout the summer months. As a result of the temperatures displayed, the ground source heat pump would use more electric energy for cooling on these hot summer nights than the baseline electric cooling system, simply because the inlet temperature to the condenser is higher.

In the winter months despite the dramatic decrease in energy use for heating, electricity is needed to operate the supplemental heating coil in the heat pump. The supplemental heating coil is shown in Figure 2.3 and is operated only when the air outlet temperature from the heat pump heating coil does not meet the zone setpoint. In this simulation, the supplemental heating coil was operated in January and February. On the days the supplemental heating coil was operated, the highest outdoor dry bulb air temperature was 24°F.

Overall, the achieved total energy use reduction is attributed to the design principles of the heat pump. With a natural gas heating system, the heat must be created first, then transferred to the zone air. In contrast, the ground source heat pump system borrows the heat from the Earth to transfer to the zone. Similarly, in the cooling season, an electric cooling coil must rely on the arduous work of the condenser fan to dispel heat from the refrigerant. But the ground source heat pump system simply transfers that heat absorbed from the zone air back to the Earth as it acts as a heat sink. In summary, the heat pump only works to transfer the heat from one location to another, while a traditional HVAC system must create the transfer medium. As shown in Figure 2.9, the Earth acts as a free heat sink.

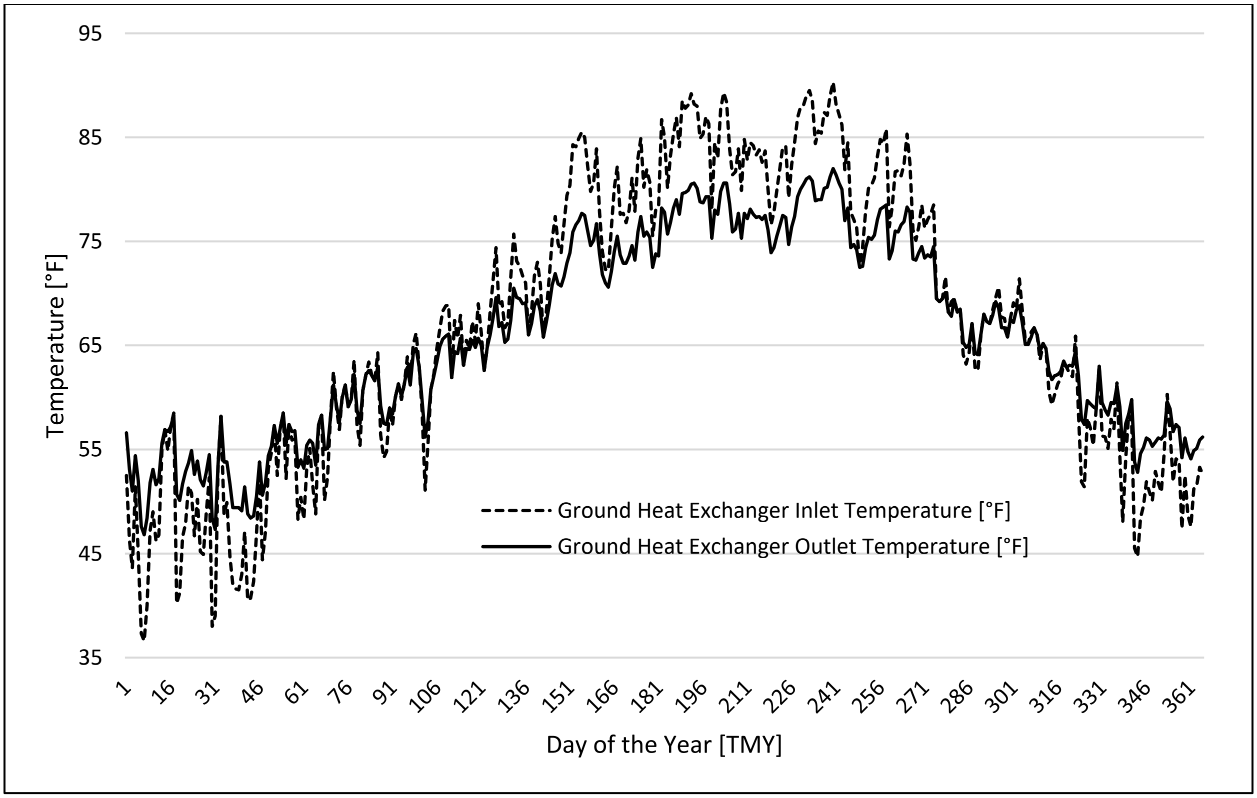


Figure 2.9 Inlet and Outlet GSHP Condenser Temperatures

In the heating season, the inlet temperature to the ground heat exchanger is lower than the outlet temperature, due to the borrowing of heat to heat the zone. In the cooling season, the inlet temperature to the ground heat exchanger is higher than the outlet temperature, due to the rejection of heat to cool the zone. This data from the EnergyPlus™ simulation verifies the proper and effective functioning of the GSHP system.

2.5.2 Payback Period Analysis

Using Equation 2.12, the initial capital investment after incentives was calculated with $Cost_{cb}$ = \$16,000, in_1 = 30% tax rebate and in_2 = \$250 rebate. The incentives for Tennessee are defined in Table 2.7. Therefore, $Cost_{ca} = \$16{,}000 - [(0.30)(\$16{,}000) + \$250] = \$10{,}950$.

Annual savings (AS) is determined by multiplying the annual energy consumption savings [kW] by the local utility rates [$/kWh] shown in Table 2.6. As displayed in Figure 2.7, the total HVAC annual metered energy consumption reduction for the prototype home during a Typical Meteorological Year (TMY) is 6,780 kWh. Therefore, $\mathrm{AS} = (6{,}780\ \mathrm{kWh})(\$0.1070) = \$725$ per year for the prototype home. Equation 2.12 is then used to determine the SPP.

It should be noted that operation and maintenance costs were not considered in the payback period analysis. ASHRAE Applications 2019 [54] states that estimating operation and maintenance costs for HVAC systems can be erroneous due to the many factors that require consideration. These factors include, but are not limited to, service environment, local seasonal conditions, geographical location, and the regional market cost of labor. For these reasons, this study treats operation and maintenance costs as a neutral component for the payback period analysis.

Equation 2.14 is used to calculate the DPP for two different discount rates. Figure 2.10 displays the DPP for each discount rate.

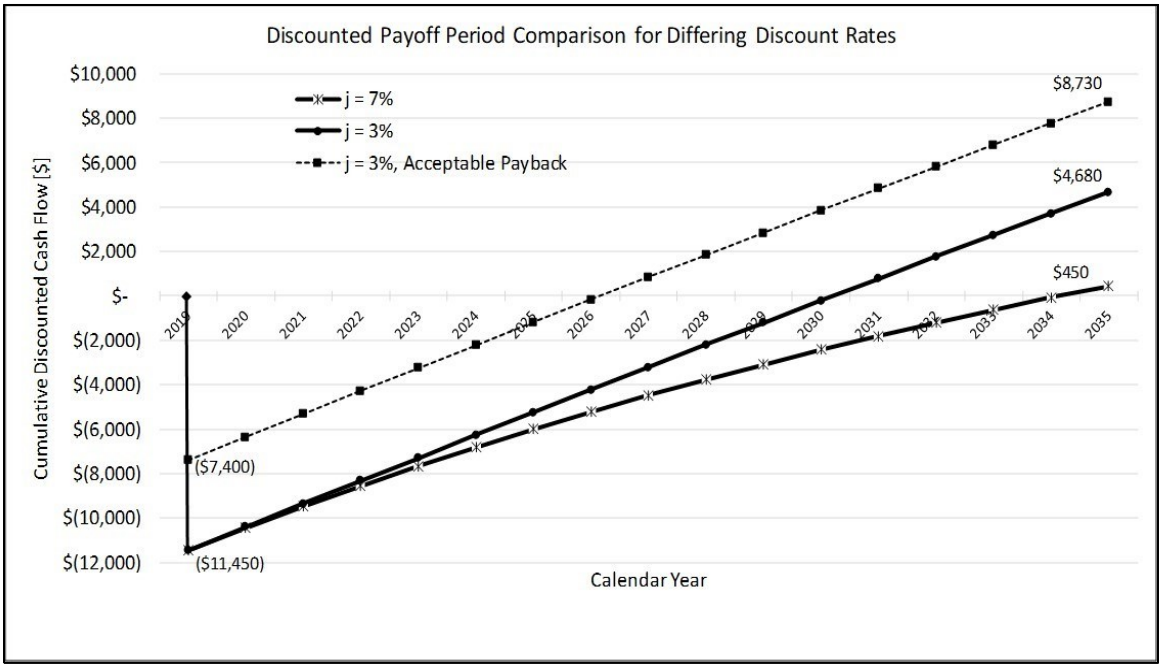


Figure 2.10 Discounted Payoff Period Comparison | Memphis, TN

Interestingly, the SPP and DPP with 3% discount rate are comparable. However, using the 7% discount rate has an immense effect on the projected payback period, extending the duration over 25 years. Table 2.10 displays payback period results and comparison.

Table 2.10 Payback Period Comparison Between SPP and DPP

Simple Payback Period (SPP)	**Discounted Payback Period (DPP)**		
	j = 3%	*j* = 7%	*j = 3%, Acceptable Payback*
15.1 years	15.8 years	25.6 years	7.2 years

Even a simple payoff period of 15.1 years will deter many homeowners from transitioning from fossil fuel energy to renewable geothermal energy. The obvious next step is to determine what payback period consumers are willing to accept, and ultimately how this payback period translates into increased financial support. Newell and Siikamaki [31] conducted a study surveying United States homeowners to define this acceptable payback period for energy efficiency home improvements. The technology product proposed in the survey was a high-efficiency water heater. A water heater replacement project is smaller in magnitude than an HVAC system replacement project, yet they can be compared because annual savings and capital investment are proportional. The water heater project costs less, but the annual savings are lower; the geothermal HVAC system costs more, but the annual savings are higher. For this reason, the payback period results from Newell [31] are used for this analysis. The survey stated that homeowners desire to recover the initial investment in energy efficiency projects in a mean of 3.5 years and 1.9 years standard deviation. Adding one standard deviation is a payback period of 5.2 years, and adding three standard deviations is a payback period of 9.2 years. Using the middle value for this example yields and acceptable payback period of 7.2 years. Newell [31] proves that this value will vary based upon household income, home size, and even race and ethnicity of the homeowner. Using the discounted payback period from Section 2.4.2.2 in reverse yields an initial capital investment of only $\$7{,}400$ to recover the initial investment in 7.2 years. For a system that was estimated to cost $\$16{,}000$ before incentives, a financial support package of $\frac{\$7{,}400}{\$16{,}000}=46.25\%$ would be necessary. This acceptable payback and cash flow of this ideal scenario is shown on Figure 2.10. By the year 2035, the homeowner that received the acceptable payback scenario will have recovered the initial investment plus $\$8{,}730$. In addition to the federal government 30% tax rebate, an additional 16.25% is required for the acceptable payback in this example. When examining other homes and climate zones, these values will vary by construction costs and energy savings.

As part of a study on geothermal district heating systems, Reber et al. [8] estimated the lifetime of a geothermal system to be 30 years. Based on this estimation, a system installed in 2019 will reach the end of its useful life in 2049. Extrapolating the cash flow analysis in Figure 2.10 to the year 2049, Table 2.11 displays the overall savings at the end of the system lifetime for the various financial scenarios already discussed.

Table 2.11 Overall System Lifetime Savings

Financial Method	**Discount Rate**	**Pre-Incentive Investment**	**Post-Incentive Investment**	**Overall System Lifetime Savings**
DPP	$j = 7\%$	$16,000	$11,450	**$5,850**
DPP	$j = 3\%$	$16,000	$11,450	**$17,695**
DPP, Acceptable	$j = 3\%$	$16,000	$7,400	**$21,745**

The results of this study demonstrate a significant annual energy consumption reduction with a ground heat exchanger heat pump system. The model removes the electric cooling and gas heating system, replacing it with a high-efficiency heat pump and ground heat exchanger. This reduction of energy consumption aligns with homeowner cost savings resulting from lower annual utility costs. For residents in Memphis, Tennessee, this data may be used to make decisions on existing system modifications. However, whether residents choose to implement a geothermal system in their homes will largely depend upon initial installation cost, all applicable tax rebates and incentives, and ultimate payback period.

It should be noted that the results are based upon the middle of the range of installation cost per ton, reported by Lim [1]. Factors setting this study apart from existing studies are (1) location-specific heating and cooling load determination through EnergyPlus™ simulation, (2) detailed ground loop parameters considering geographical soil characteristics, and (3) incorporation of state and local financial incentives in payback period calculation. At this time, the possibility of an alternative, more affordable energy system is verified from the performance standpoint. Using the Memphis, TN model as a baseline design, the scope of this research can widen to other residential areas in diverse climate and geographical areas. The potential in other climate zones will vary greatly as will weather data, soil properties driving performance, and state-specific incentive programs. Follow on studies will investigate additional climate regions, as well as customizing the system design to reduce payoff period.

Computer-aided simulations are a valuable tool for predicting experimental data. The experimental data validating the results in this study can be collected as residential geothermal heat pump systems are put into practice. The valuable contribution of this study is the definition of a prescriptive procedure outlined in Table 2.1 and executed through the Memphis, TN example. is delivery of a procedure. This procedure provides a template for homeowners to become more informed on the technical and economic feasibility of residential geothermal technology at their home and community. Through EnergyPlus™, any residential building's features, construction characteristics, and geography can be input for a customized energy savings analysis. After savings are known, the template provides a guide to calculate the whole life cycle cost of the energy efficiency upgrade. The procedure will predict the real applications, allowing a potential customer gain confidence in the decision to retrofit an existing system to a higher efficiency, geothermal system.

By marrying thorough soil properties data [42], sophisticated borefield design methods [35], and economic policies [49], this study delivers a novel procedure template to analyze a diverse spectrum of residential buildings. All the components of an accurate techno-economic feasibility of the technology are blended together in this chapter.

2.6 Chapter Summary

A prototype home provided by the Department of Energy is the home used in this geothermal heat pump energy investigation [37]. The home resides in Memphis, Tennessee. The study within provides highly location-specific results due to calculations of exact bore length. This design specification is determined by thorough soil property identification by type, density, porosity, and undisturbed ground temperature. Actual residence heating and cooling loads were used in energy simulations. The union of precise ground characteristics, accurate home energy use, and region-specific incentive analysis create a confidently accurate energy consumption savings and annual cost savings to the potential customer.

Modeling and analysis within EnergyPlus™ display evidence of 26% energy use reduction when a geothermal heat pump system replaces the original electric cooling and gas furnace heating system. Comparison between the initial monthly energy consumption and the modified monthly energy consumption reveal the reduction in electric and gas usage. Despite the energy savings, the payoff period resulted in a duration of up to 15 years, much longer than many homeowners will find attractive. The model was tailored to the soil properties and weather data for Memphis, Tennessee. Further investigation will include optimization of the borefield parameters and insertion of additional locations' parameters into the template developed within this study.

CHAPTER III

STATE OF THE NATION: CUSTOMIZING ENERGY AND FINANCES FOR GEOTHERMAL TECHNOLOGY IN THE UNITED STATES RESIDENTIAL SECTOR

This chapter broadens the work performed in CHAPTER I to climate zones across the United States. As proved, geothermal residential heating and cooling systems have undeniable potential savings. The possibilities of the energy savings with a geothermal heat pump system is well-established in the commercial and residential sectors. Building location has a critical impact on the performance of geothermal heat pump systems and magnitude of savings. An important contribution of this chapter takes the step past technological optimization to investigate 12 climate zones across the contiguous United States. Residential homes within common neighborhoods are thoroughly analyzed by considering soil characteristics and home construction features. Within these climate zones, federal and all local incentive programs are quantified to determine an accurate expectation for capital investment payback period, a critical factor for system attractability. Ultimately, a climate zone is classified as either a promising or poor candidate for residential geothermal technology based on data from previously conducted human interest polls regarding payback period on energy savings investments. With such lasting potential delivered to the hands of consumers, geothermal energy use still experiences slow implementation. This chapter conducts a study integrating data on technology, finances, and human nature to identify the prevailing barrier to widespread geothermal execution. Solid evidence on energy and monetary savings reveals the dominant barriers are initial capital investment and long payback period. This chapter highlights the immense positive impact that local incentives have on affecting these two prevailing deterrents.

3.1 Introduction

This chapter focuses on the energy savings and capital investment of residential buildings representing 12 climate zones across the contiguous United States. The objective is to investigate climate zones as viable or nonviable in terms of cost and savings. Closing the gap of previous studies, this study considers site-specific soil characteristics, home construction materials, and local federal financial incentive programs. The buildings representing each climate zone are actual residential homes within the respective city limits. The three factors of soil, structure, and incentives make significant impacts on the viability of a climate zone for geothermal space heating and cooling. This chapter provides knowledge required for an informed, confident choice to be made under the roofs of home across the climate zones of the United States.

Prior research made ardent strides toward the technical feasibility of geothermal space heating and cooling. Specifically, geothermal space heating and cooling is achieved with a ground heat exchanger (GHE) and water to air heat pump (WAHP). Together, these two components make up the geothermal heat pump (GHP), also referred to as ground source heat pump (GSHP). Liu et al. [1] presented the most relevant study by investigating buildings in both the commercial and residential sectors across the United States in 13 climate zones. The study used county-level energy use data and a borehole sized to maintain a range of ground loop water temperatures. The simulation tool and method for sizing the heat pump is unknown. Unlike Liu [1], this chapter zooms in on a specific residential neighborhood in each city to obtain ground parameters and determines heating and cooling loads from a simulation of the existing system in that climate zone.

Liu [1] concluded that the knowledge would improve in breadth by a more site-specific GHE design as well as consideration of local financial incentive programs. These two recommendations are executed in this investigation to achieve more site-specific knowledge. In addition to the loads and simulation methods, a properly sized GHE and heat pump has been verified in prior research. Sagia et al. [11] emphasized the proper sizing of the GHE for energy savings. The subject of the analysis was a building in Greece, but the results are relevant globally. Simulation efforts focused on sizing the GHE, but did not attempt to determine the optimal heat pump capacity. The critical conclusion to a study by Eslami-Nejad et al. [10] was that a properly sized GSHP makes all the difference in energy consumption. Augmenting methods from Sagia [11] and Eslami-Nejad [10], this study performs the simulations with optimal heat pump sizes as dictated by EnergyPlus™ to tailor performance and climate zone-specific designs.

In the investigation, a simple payback (SPP) period method calculated the payback periods. The SPP does not consider the time value of money. Use of the SPP for energy investments is a better fit for some investigations than others. Zhang et al. [34] conducted a review of incentive analysis and payback period for solar photovoltaic system in the U.S. Although the sector was commercial rather than residential, Zhang [34] believed the SPP was a suitable method of payback analysis because of the long-term variability of available financial incentives. Due to the state-by-state incentive analysis, the SPP was determined to be a metric indicative of capital investment payback period. However, a follow-on study by Zhang et al. [55] added the discounted payback period (DPP) tool to the investigation and cash flow analysis. The findings revealed the time value of money consideration provided reliable payback periods and lifetime system cashflows. Learning from Lim [14] and Zhang [34] [55], this study implements two different payback period methods of calculation that both take into account inflation and the change in value of the current U.S. dollar.

A compelling publication assessed the strategies that current research could be improved. In Lim [5], it is suggested that more accurate results for system performance could be achieved with simulation tools such as EnergyPlus™, site-specific soil characteristic consideration, and local plus federal incentive programs. These three recommendations are active components of this study, and were implemented in an investigation by Neves et al. [56] for a single residence in Memphis, TN. Results for this climate zone 3A residence proved a 26% energy use savings with a geothermal heat pump system over a traditional baseline system. The outcome of the study by Neves [56] in one location sparked a desire to perform the analysis nationwide across many climate zones, and became the leading motivation for this chapter. To create a logical method of analysis of many locations, a study by Zhang et al. [57] provided a valuable guide. A nationwide review of combined heat and power (CHP) systems were evaluated for technical and financial performance. The structure of the study was mirrored in this investigation by defining many cities with varying climate conditions, performing a technical analysis, analyzing applicable incentives both federal and local, and defined a payback period. Zhang [57] presented an admirable method of analysis for replication for similar energy studies of different renewable technologies and sectors.

As outlined, the technical knowledge is available, but the financial and site-specific customization component is enhanced in this investigation, providing the most comprehensive knowledge base for the United States climate zones. The roadmap of this study fills in the details introduced. Section 3.2 outlines the strategy of choosing the cities to represent the 12 diverse climate zones and ensure high variability. Simulation of the baseline system is performed in Section 3.3, as well as the methods for sizing the replacement GSHP system. Payback analysis methods are also introduced in Section 3.3. Section 3.4 reports the results of the simulations, choice of heat pumps by climate zone, and payback period. Conclusions and tactics to use the learned knowledge are presented in Section 3.5. Specific objectives are identification of viable climate zones for geothermal space heating and cooling based upon techniques more sophisticated that previous studies in site selection, space loads profiling, customized GSHP system, and all incentive programs included in payback analysis. Simulations result in attractive financial propositions, depending on the climate zone. This study provides a comprehensive overview of the technical and financial feasibility of geothermal systems in homes representing diverse climates, and a guide for analysis methods for future locations.

3.2 City Selection and Building Description of Suburban Residences

Identification of representative cities from 12 climate zones was performed by combining geographical, temperature, and humidity classifications. Choosing a diverse collection of cities in these 3 categories was imperative to this study, as differences in all can greatly affect the viability of a region for geothermal heating and cooling technology. Figure 3.1 and Figure 3.2 were used to choose 12 cities based on a variety of temperature, humidity, and geographical parameters. Figures 3.1 and 3.2 were published by U.S. Department of Energy Efficiency & Renewable Energy in their Guide to Determining Climate Regions by County [58]. Figure 3.1 groups regions of the continental United States together based upon temperature and humidity.

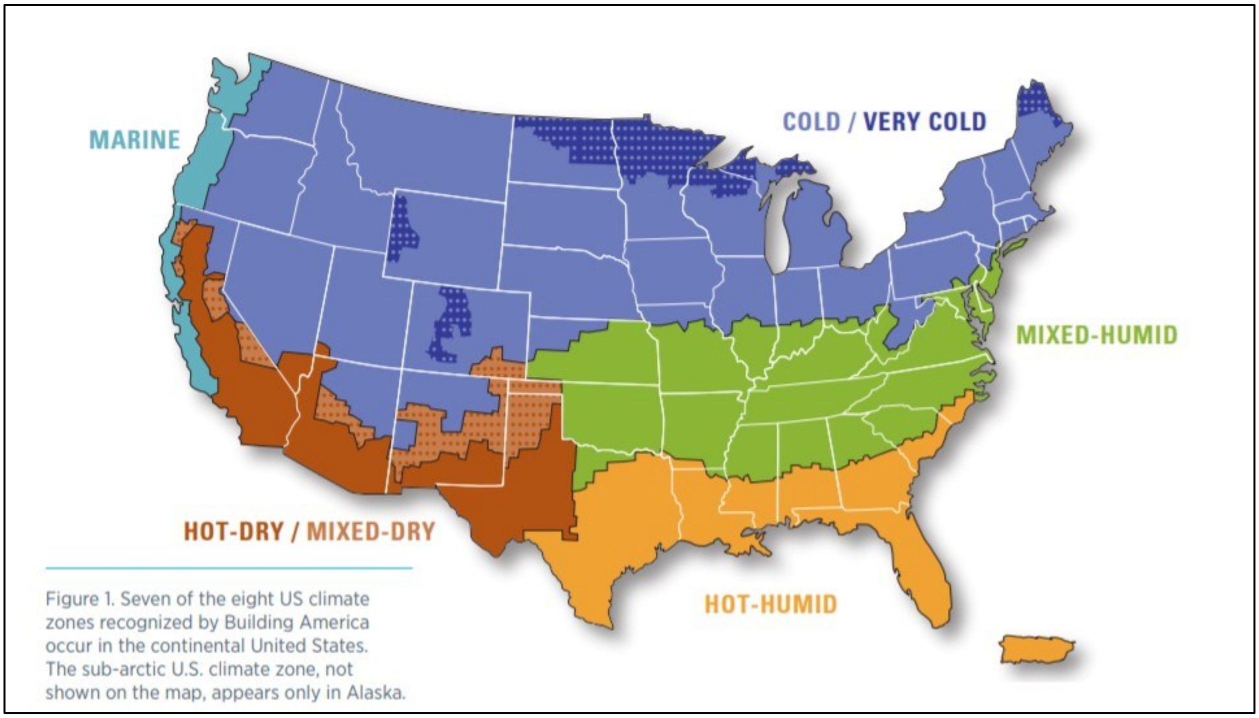


Figure 3.1 Climate zones by temperature and humidity [58]

U.S. Department of Energy, “Guide to Determining Climate Regions by County,” vol. 7.3, no. August, 2015.

Information extracted from Figure 3.1 was compared to the data presented in Figure 3.2, which provides a nomenclature system for regions of the U.S. by temperature, humidity, as well as common latitude. For example, zones 3 and 4 in Figure 3.2 appear as one grouping labeled “mixed-humid” in Figure 3.1. Similarly, the “hot-humid” grouping in Figure 3.1 is unmerged in Figure 3.2 as Tropical or Subtropical. Therefore, to generate a full array of climactic characteristics, cities were chosen with the consultation of both classification techniques. The resulting group of 12 cities aims to represent the most diverse collection of climate and geographical characteristics.

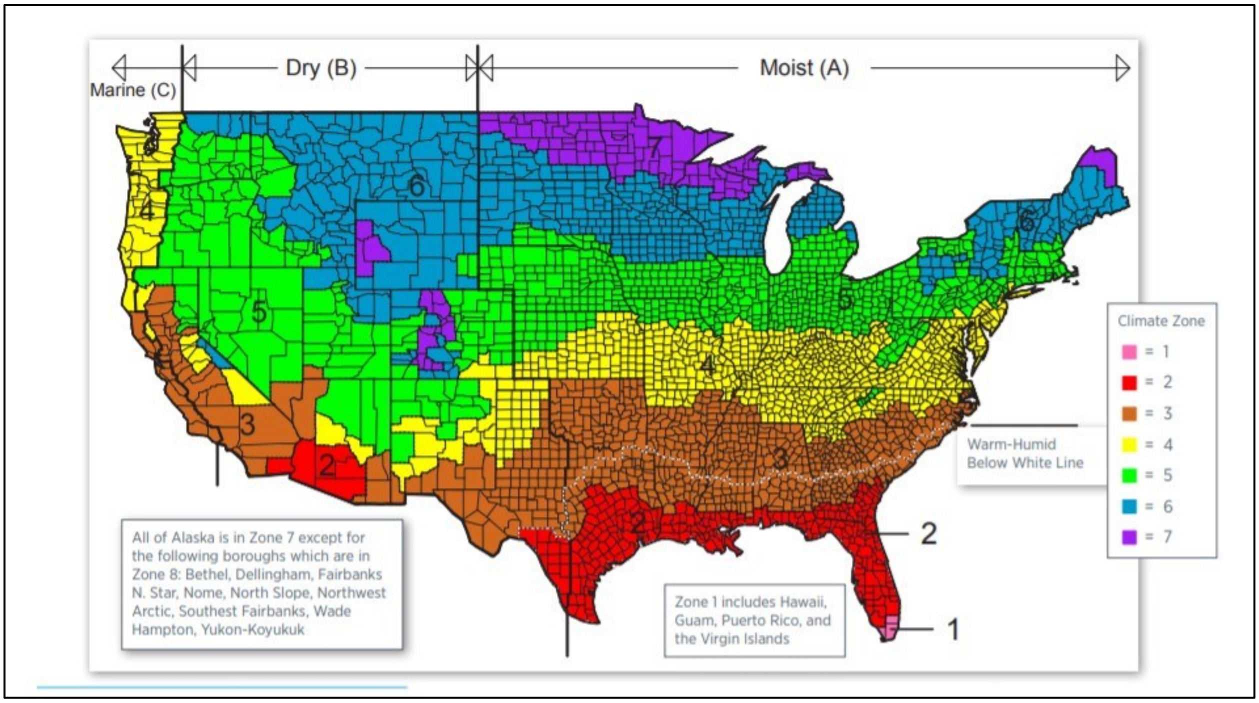


Figure 3.2 Climate Zones by Longitude and Latitude [58]

U.S. Department of Energy, "Guide to Determining Climate Regions by County," vol. 7.3, no. August, 2015.

Based on the research and classification of climate zones presented in Figure 3.1 and Figure 3.2, the alphanumeric nomenclature shown in Figure 3.3 was created and is used in this study. The number designates the geographical classification by latitude and longitude per Figure 3.1 and Figure 3.2 [58]. The letter represents moisture classification A, B, or C.

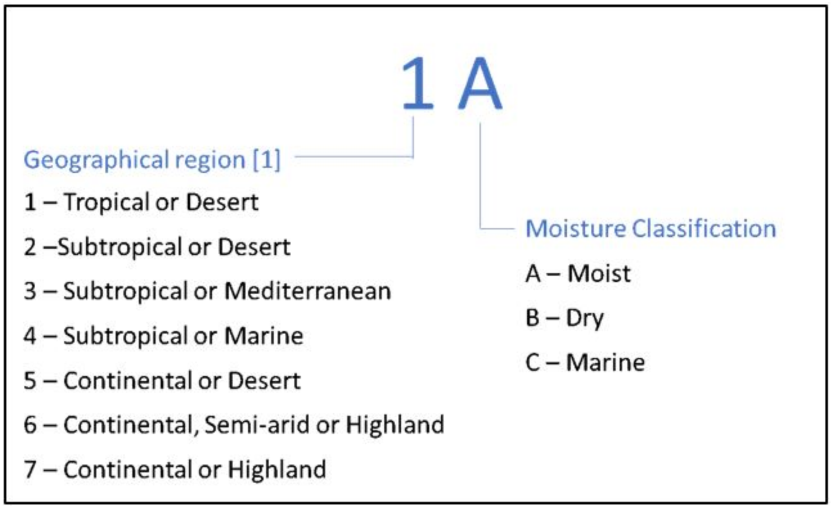


Figure 3.3 Nomenclature Guide for Cities of Interest

Considering all the presented the climate classification research, the 12 cities shown in Table 3.1 were chosen to achieve a diverse collection of cities by temperature, humidity, and geographical location. Table 3.1 also displays undisturbed ground temperatures of the selected cities, as this parameter is significant for the geothermal system analysis [59].

Table 3.1 Cities Representing Diverse Climate Regions

Classification	Description	Moisture Classification	City | State	Undisturbed Ground Temperature
1A	Tropical Hot-Humid	Moist	Miami | FL	62
3A	Subtropical Mixed-Humid	Moist	Memphis | TN	78
2B	Subtropical Hot-Dry	Dry	Phoenix | AZ	73
3B	Midlatitude Desert Hot-Dry	Dry	Las Vegas | NV	69
3C	Mediterranean Hot-Dry	Marine	Los Angeles | CA	64
4A	Subtropical Mixed-Humid	Moist	Baltimore | MD	57
4C	West Coast Marine	Marine	Portland | OR	54
5B	Desert Cold	Dry	Reno/Tahoe | NV	50
6B	Semi-arid Steppe Cold	Dry	Helena | MT	47
5A	Continental Cold	Moist	Des Moines | IA	53
7A	Continental Very cold	Moist	Duluth | MN	41
7B	Highland Alpine Very Cold	Dry	Gunnison | CO	52

Figure 3.4 displays the geographical variety of the cities on a map of the United States. Cities range far north, south, east, and west. The selection encompasses combinations of temperature, humidity, and location to allow a comprehensive analysis of geothermal heating and cooling systems by climate zone.

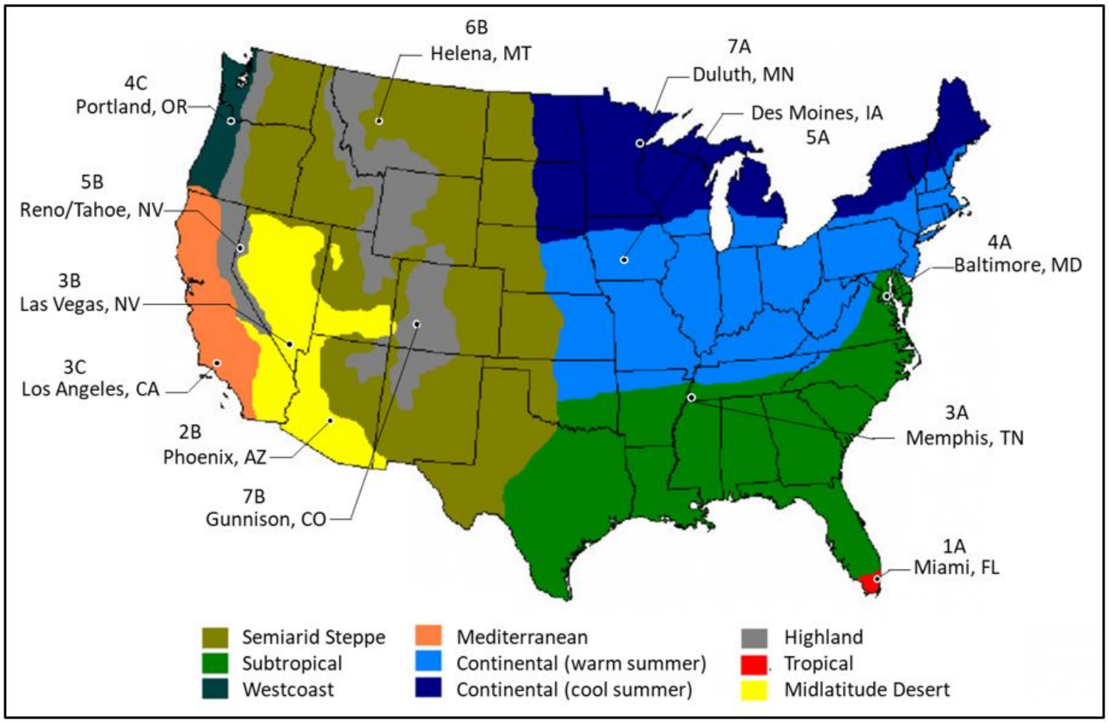


Figure 3.4 Map of 12 Diverse Climates [60]

The graphic was created by labeling the 12 cities of interest on the background climate map of the U.S. Map source: T. Abichou, C. Wang, T. Kormi, and J. Chanton, "A novel approach to estimate methane oxidation in interim landfill covers across the USA.," *Int. J. Environ. Waste Manag.*, vol. 15, no. June, p. 309, 2015.

To further validate the diversity of the selected cities, the 12 locations were compared by seasonal temperatures and relative humidity. The cooling season (summer) was considered separately from the heating season (winter) through the analysis of cooling degree days (CDD) and heating degree days (HDD), respectively. CDD and HDD values are a measure of the extremity of temperatures in a given location. Both are measured by comparing a day's average temperature relative to 65°F. The value of CDD is equal to the number of degrees above 65°F. The value of HDD is equal to the number of degrees below 65°F. For example, the mean temperature in Memphis, Tennessee on September 27, 2019 was 93°F. Therefore, on this day CDD = 93°F –

65°F = 28 CDD [61]. Similarly, the mean temperature in Portland, Oregon on January 16, 2020 was 37°F. Therefore, on this day HDD = 65°F - 37°F = 28 HDD. A high value for CDD indicates a hotter average temperature, and a high value for HDD indicates a colder average temperature. If the CDD and HDD values for a city are low, this measure indicates a milder temperature spectrum. For this study, CDD and HDD metrics were summed, by year, for each of the 12 cities [62]. These values were graphed along with the city's average annual relative humidity (RH) published by the National Oceanic and Atmospheric Administration Center [63], which recorded morning and afternoon average relative humidity readings by month. Using these readings, the values were manually averaged over the year to determine the mean annual RH for classification purposes in this study. Results for diversity in CDD and humidity are shown in Figure 3.5. In this unique graphic, relative humidity is the x-axis and CDD is the y-axis. The crosshatch in the center bisects the range of each axis. When plotted on this coordinate system, the locations naturally populate in four quadrants. The quadrants are classified as warm/moist, warm/dry, cool/dry, and cool/moist. The cool/moist quadrant houses the greatest quantity of cities, but there are extremes in each of the four. See Figure A.1 in Appendix A, for a more traditional x-y coordinate graphic for displaying diversity in the cooling season.

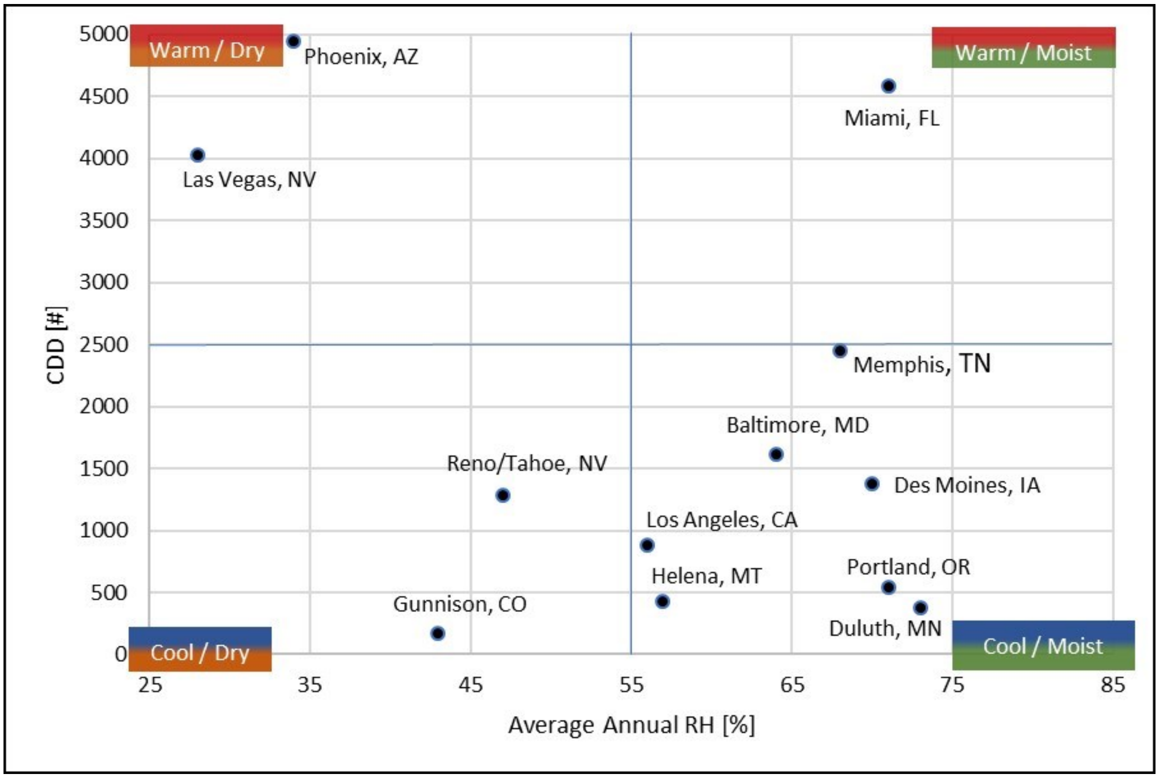


Figure 3.5 CDD vs. Humidity Data Grid

Cooling degree days data found at: Energy Star, "Degree Days Calculator," *Portfolio Manager*. [Online]. Available: https://portfoliomanager.energystar.gov/pm/degreeDaysCalculator. [Accessed: 25-Feb-2020].

Complementary to Figure 3.5 showing cooling season data, Figure 3.6 depicts diversity in heating data. Relative humidity is the x-axis and HDD is the y-axis. The crosshatch in the center bisects the range of each axis. When plotted on this coordinate system, the locations populate all four quadrants as they did for CDD data. The quadrants are classified as cold/moist, cold/dry, warm/dry, and warm/moist. The warm/moist quadrant houses the greatest quantity of cities, but the rest are spread between the remaining three quadrants.

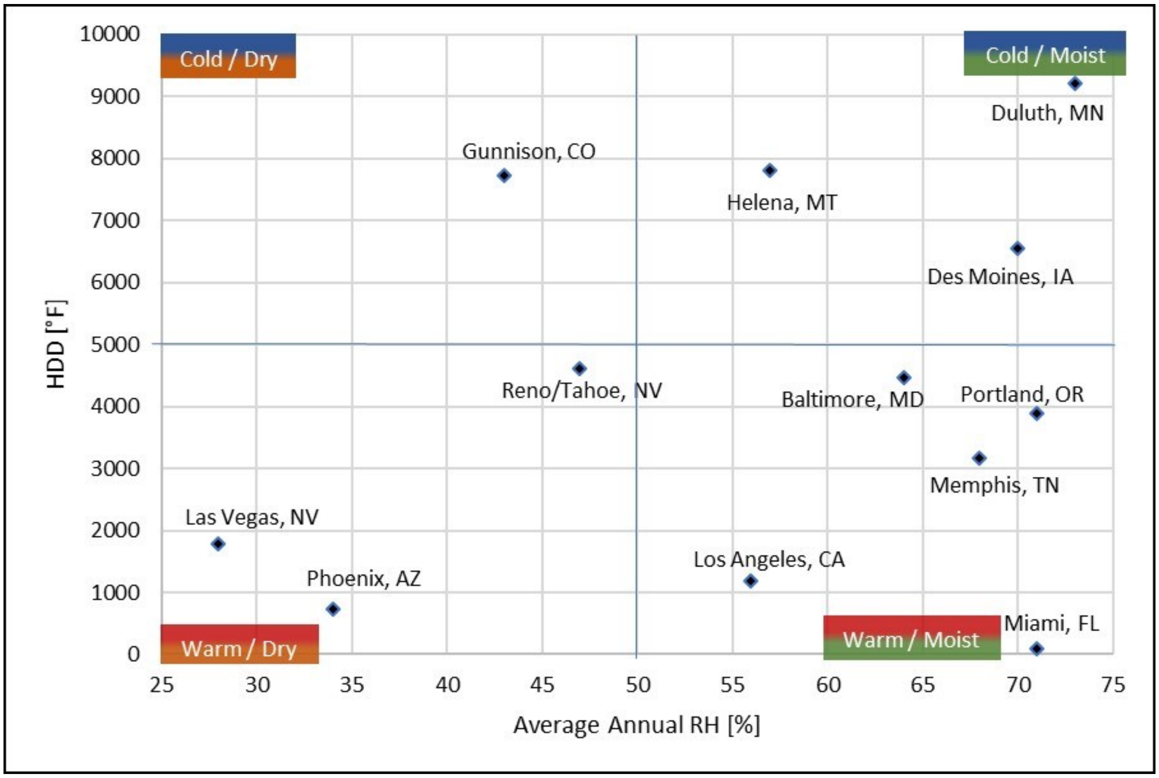


Figure 3.6 HDD vs. Humidity Data Grid

Heating degree days data found at: Energy Star, "Degree Days Calculator," *Portfolio Manager*. [Online]. Available: https://portfoliomanager.energystar.gov/pm/degreeDaysCalculator. [Accessed: 25-Feb-2020].

The heating season is a significant area of interest for a geothermal heating system, as the heat pump eliminates the need for natural gas. Therefore, verifying a diverse collection of cities for winter conditions is critical for a comprehensive analysis. Results for diversity in HDD and relative humidity are shown in Figure 3.6. As shown, the selection includes cities with high HDD and high humidity (Duluth, MN), low HDD and high humidity (Miami, FL), low HDD and low humidity (Phoenix, AZ), and high HDD and moderate humidity (Gunnison, CO). Other cities fall in between these extremes with one of the two parameters moderate. See Figure A.2 for a more traditional x-y coordinate graphic for displaying diversity in the heating season.

Aside from the degree days and humidity variation, several other characteristics of the location and home itself contribute to the selection diversity. The elevation, annual average air temperatures (T_{OA}), and maximum difference in monthly average air temperatures ($\Delta T_{OA,max}$) all affect the building energy performance. Temperature data is embedded in the prototype home construction characteristics building file from the U.S. Department of Energy [37]. Construction features also affect the heat transfer characteristics. Window U-factor is a measure of the window assembly's conductance of heat. A higher U-value corresponds to a faster transmission of heat through the window assembly, which typically includes ultraviolet coating, two or three panes of glazing, and air gaps in between the panes. The U-value and the R-value have an inverse mathematical relationship. Therefore, the basement insulation R-value is a measure of the material's resistance to heat transfer. The higher the R-value, the greater the insulating property. Conductivity and insulation values are reported through ASHRAE 90.2 Energy-Efficient Design of Residential Low-Rise Buildings [64]. A sampling of these characteristics is shown in Table 3.2.

Table 3.2 Table of Differences Affecting Home Energy Use

City | State	Elevation	Window U-factor	Basement Insulation R-value	Annual Average T_{OA}	$\Delta T_{OA,\,max}$
	[ft]	[Btu/h-ft^2-°F]	[ft^2-h-°F/Btu]	[°F]	[°F]
Portland | OR	20	0.32	12.9	54.0	28.8
Miami | FL	36	0.50	0.0	76.1	51.9
Los Angeles | CA	98	0.35	12.9	62.3	11.3
Baltimore | MD	148	0.35	12.9	55.7	46.4
Memphis| TN	266	0.35	12.9	62.6	43.6
Des Moines | IA	958	0.32	18.9	50.3	55.8
Phoenix | AZ	1106	0.40	0.0	74.8	43.0
Duluth | MN	1421	0.32	18.9	39.1	55.4
Las Vegas | NV	2126	0.35	12.9	67.6	45.5
Helena | MT	3829	0.32	18.9	44.8	45.9
Reno | NV	4403	0.32	18.9	15.7	44.6
Gunnison | CO	7674	0.32	18.9	39.5	51.3

The building models used in this study for simulation are provided by the U.S. Department of Energy for use with EnergyPlus™ simulation engine [37]. Each file is populated with building specific construction data. Within the files are varying heat transfer surface orientations, represented by x, y, and z coordinates in space. Example of building surfaces include floor, ceiling, interior flooring, roof surfaces, exterior walls, below ground crawl wall, and building vertices coordinates. Wind speed and wind direction also vary by city and season.

3.3 Materials and Methods

A methodical process to gather data, run simulations, compare performance, and generate a financial forecast allowed for efficient repeatability across the climate zones of the United States. A goal of this research is to create a template that can easily produce results for any home in any city. Table 3.3 displays the steps that collectively make up the method of this chapter. The major steps listed may be comprised of several intermediate tasks not shown.

Table 3.3 Sequential Summary of Analysis Method

STEP	METHOD
1	Gather data from prototype homes based on weather profiles
2	Generate baseline energy use data with existing HVAC system
3	Gather thermal and physical soil properties from 12 locations
4	Design customized borehole depth based upon soil properties and ground loads
5	Modify EnergyPlus™ residence files to replace existing system with GHP system
6	Run simulations with new GHP system
7	Compile energy use data with new GHP system to compare to existing system
8	Determine monthly savings with local utility cost [$/kWh]
9	Apply local incentives to each location to arrive at payback period and system savings
10	Provide metric to evaluate expected consumer acceptance of payback results
11	Determine steps for further knowledge precision

3.3.1. Geothermal System Analysis

3.3.1.1 Ground Heat Exchanger Design

A single, vertical bore was the GHE type in this geothermal analysis. Other types include horizontal or slinky-style borefields. Both alternatives require significant land area. The vertical borefield is the focus in this study because the selected cities are chosen from urban and suburban residential areas, where lot sizes are smaller. The residential buildings selected from each climate zone in this study were from urban and suburban areas, rather than rural. The feasibility of a horizontal borefield is unlikely for these homes, due to space limitations. Therefore, vertical single-bore ground heat exchangers were the chosen configuration.

For all 12 cities in this study, a custom borehole length was calculated with the consideration of ground loads and soil characteristics. The ground loads were determined by running a simulation for each city's prototype home and weather file with the existing electric cooling and natural gas heating system. The single-family model prototype homes and weather files were provided by the U.S. Department of Energy [37] [65]. The peak ground load is the heat rejection or absorption necessary during either the heating or cooling season, whichever was higher.

Soil characteristics vary between the 12 locations. Thermal conductivity values for each location were determined through the combined use of the Web Soil Survey and ASHRAE Fundamentals [42]. Dominant soil type and water content was determined by defining a geographical Area of Interest (AOI) and running the reports on the soil data. With the two input values of soil type and water content, thermal conductivity was determined from ASHRAE Fundamentals.

Defining an AOI as large as a city's boundaries resulted in too many soil types, and it became difficult to distinguish the dominant type for a residential neighborhood. Therefore, Multiple Listing Services (MLS) was consulted to determine real, residential neighborhoods that have homes the size of the prototype home. The AOI for each city was then zoomed into a smaller geographical region of the city. This smaller region focused on a neighborhood or community, where the dominant soil type was more distinguishable. Table 3.4 below identifies the street and zip code in each target city around which the soil samples were investigated for predominant soil type, corresponding thermal conductivity, k [66], and soil specific heat capacity, c_p [43] [47].

Table 3.4 Residential Building Locations for Soil Characteristic Analysis

Zone	City | State	Street	Zip Code	Predominant Soil Type	k [66] [W/m•K]	c_p [43] [47] [J/kg•K]
1A	Miami | FL	NW 82nd Terrace	33150	Sand	1.586	2465
3A	Memphis | TN	N Angela Road	38117	Silt loam	2.307	3308
2B	Phoenix | AZ	W Camino Acequia	85051	Clay loam	1.442	1995
3B	Las Vegas | NV	Capistrano Avenue	89169	Sandy loam	1.730	2418
3C	Los Angeles | CA	Lancaster Avenue	90033	Clay loam	1.009	1396
4A	Baltimore | MD	Kildaire Drive	21234	Sandy loam	2.163	3152
4C	Portland | OR	NE 35th Avenue	97212	Silt loam	2.163	3199
5B	Reno | NV	Shale Court	89503	Sandy loam	2.307	2257
6B	Helena | MT	Hillsdale Street	59601	Loam	1.586	2264
5A	Des Moines | IA	24th Street	50311	Loam	1.730	2469
7A	Duluth | MN	N Robin Avenue	55811	Silt loam	1.298	1920
7B	Gunnison | CO	County Road 20	81230	Stony loam	2.307	3585

Street addressed obtained from Multiple Listing Services (MLS) at http://www.mls.com/. Homes for sale of approximately 2400 SF in the urban or suburban areas of each city were identified and used as the subject property.

Using ground heating loads, the borehole length was calculated using the method presented by Philippe and Bernier [35]. In addition to a custom ground heat exchanger size, the cooling and heating capacity of the heat pump itself is a significant contributor to the ultimate energy consumption savings [10]. To achieve a truly customized analysis, the recommended design capacity was determined through the EnergyPlus™ autosize function, then resimulated with the autosize specified as the actual capacity. Once determined, the program was tuned to reflect the performance characteristics of that specific size equipment.

3.3.1.2 Heat Pump Input Parameters

The heat pump performance curves were generated by compiling performance data from 5 market-leading, reputable heat pump manufacturers by EnergyStar [67]. Curves were generated for three heat pump capacities of 024, 036, and 048 [68][69][70][71][72]. These numerical values correspond to the nominal cooling load. Efficiency parameters are shown in Table 3.5.

Table 3.5 Heat Pump Average Efficiency Values

Model Number	Cooling EER	Heating COP
HP024	17.4	3.84
HP036	17.6	3.82
HP048	16.9	3.80

Average EER and COP values obtained by taking the mean of each value from all five geothermal heat pump manufacturers. They represent the current market leading manufacturers in energy-efficiency per https://www.energystar.gov/.

Simulating various heat pump sizes for each residential building requires specific inputs to EnergyPlus™ in the form of heat pump coefficients, coefficients of performance (COP), and design water flow rate. Heat pump coefficients are calculated by a supplementary spreadsheet program provided by EnergyPlus™ [73]. The program requires detailed performance data at varying environment conditions that is typically provided by the heat pump manufacturer. From the data, the coefficient generator outputs values that then become inputs to EnergyPlus™ for use with the Water-To-Air Heat Pump Equation Fit object. Unique heat pump coefficients were calculated for each size heat pump, for both cooling and heating performance. A puzzling revelation was discovered in the process of developing the heat pump coefficients from the performance curves. Initially, one manufacturer was chosen and all coefficients were calculated from that particular submittal data. Energy use and savings results were generated. To verify, a second manufacturer's submittal data was used to generate new coefficients. Interestingly, the usage and savings results were varied enough to cause pause. Ultimately, the top 5 manufacturers' performance data for each capacity was compiled, resulting in one set of heat pump coefficients indicative of performance data across many manufacturers. Results in this study characterize the collective market available, high-efficiency residential geothermal heat pumps. Heat pump coefficients used in this study for heating and cooling are shown in Table B.1 in Appendix B.

Determination of the heat pump coefficients for input into the simulation was a defining and tedious task, but one that proved crucial to accurate results in this study. Geothermal heat pump coefficients were generated as inputs to EnergyPlus™ simulation software. These heat pump coefficients are generated by compiling heat pump performance data from 5 market leading, high efficiency residential geothermal heat pump manufacturers. These coefficients can be used to represent a general, market available heat pump in 2-ton, 3-ton, and 4-ton capacities. Baseline prototype home energy use by city was generated by EnergyPlus™ using the prototype home download file from www.energy.gov and the respective weather file for that city. This data can be interpreted as energy use per month by certain HVAC components. The GSHP home energy use by city was generated from EnergyPlus™ and the respective city weather file. The GSHP model was created by the authors to model the alternate closed loop, GSHP system.

The general heat pump coefficients by capacity is valuable for future researchers studying geothermal heat pump performance, particularly for residential applications. They are performance curves for an overall market-available geothermal heat pump, not tied to a specific manufacturer. This data was not already available and published when this study was performed, so the availability of this information fills a gap in present data. The energy use data is useful to researchers seeking to quantify usage and financial savings for alternative energy HVAC systems. The original, or baseline, system is a DX cooling / natural gas heating traditional system. The replacement system is a ground source heat pump that has been sized accounting for soil characteristics local to specific regions of the United States.

The geothermal system required several inputs including the heat pump cooling and heating coil coefficients, ground heat exchanger parameters, soil conductivity and specific heat capacity, and borefield type. For the heat pump coefficient data, an extensive amount of data entry was required from the engineering specifications published by various heat pump manufacturers

Further insights and development of experiments are limitless with the data presented. The heat pump performance coefficients apply for any analysis of a residential geothermal heat pump that is simulated with EnergyPlus™. The data can be used as direct inputs into the Water-To-Air Heat Pump cooling coil and heating coil objects. The home energy use data is useful for further insights to compare or contrast with other cities across the country or the globe. This comparison is possible with the baseline prototype home data or the geothermal heat pump system data.

Once all construction, weather, geographical, and heat pump characteristics were input to EnergyPlus™, the simulation engine was executed. The total energy use for each scenario was compared to the energy use for the baseline electric cooling/gas heating system. Contributions to the total consumption by each system component was investigated to accurately identify where the increases and decreases occur, before and after system replacement.

3.3.2 Geothermal Heat Pump System Description

The geothermal heat pump system is represented by the schematic in Figure 3.7, originally published by Neves et al. [56]. The load side is a represented as a single zone living area, and the source side is the GHE. These two components, source side (ground) and load side (zone), intersect at the heat pump. Refrigerant and heat are transferred in one direction during the cooling season, then reverses in the heating season. This reversal is what distinguishes a heat pump from a traditional electric air conditioner, as the direction of heat flow simply changes depending on whether heat is absorbed from or rejected to the ground.

3.3.2.1 Heating Mode

In the cold season, the GHP operates in heating mode. In both modes, the heat transfer medium from the ground to the heat pump is water. In heating mode, heat is absorbed from the ground by the water and the heat is delivered to the heat pump. Inside the heat pump, the warm water exchanges the heat to the refrigerant in the refrigerant coil. This exchange marks the location that the source side intersects the demand side. In the heating mode, the water is acting as the evaporator for the refrigerant as it delivers it heat. The hot refrigerant is then superheated by the compressor. Superheated refrigerant runs through the air handling unit (AHU) where a fan blows mixed air needing heat over the hot refrigerant coil. The mixed air is a combination of return air (RA) from the zone and outside air (OA). The AHU maintains proper volume of return RA and OA to achieve human comfort and meet ventilation requirements. A supplemental heating coil may contribute to the air prior to delivery to the zone. The call for supplement heat depends on the outside air temperature and the desired temperature of the air leaving the heating coil. The desired outcome is warm air delivered to the zone as it has received heat from the refrigerant and supplemental heater, if necessary. Cooler refrigerant exits the zone and is chilled further by the pressure drop across the expansion valve. The refrigerant then transfers to the water/refrigerant heat exchanger to begin absorbing heat from the ground water. The cycle begins again. Cold seasons vary in calendar months and duration between the selected cities.

3.3.2.2 Cooling Mode

In the warm season, the GHP operates in cooling mode. In cooling mode, heat is rejected to the ground by the water and the cooler water returns to the heat pump. Inside the heat pump, the cool water absorbs heat from the refrigerant in the refrigerant coil. In the cooling mode, the water is acting as the condenser for the refrigerant absorbs the refrigerant's heat. The cooler refrigerant is then chilled further by the pressure drop across the expansion valve. Chilled refrigerant runs through the AHU where a fan blows warmer mixed air over the cool refrigerant coil. The desired outcome is cold air delivered to the zone as it has rejected heat to the refrigerant. The now hot refrigerant is then superheated by the compressor. The refrigerant then enters the water/refrigerant heat exchanger to begin rejecting heat to the ground water. The cycle begins again. Warm seasons vary in calendar months and duration between the selected cities.

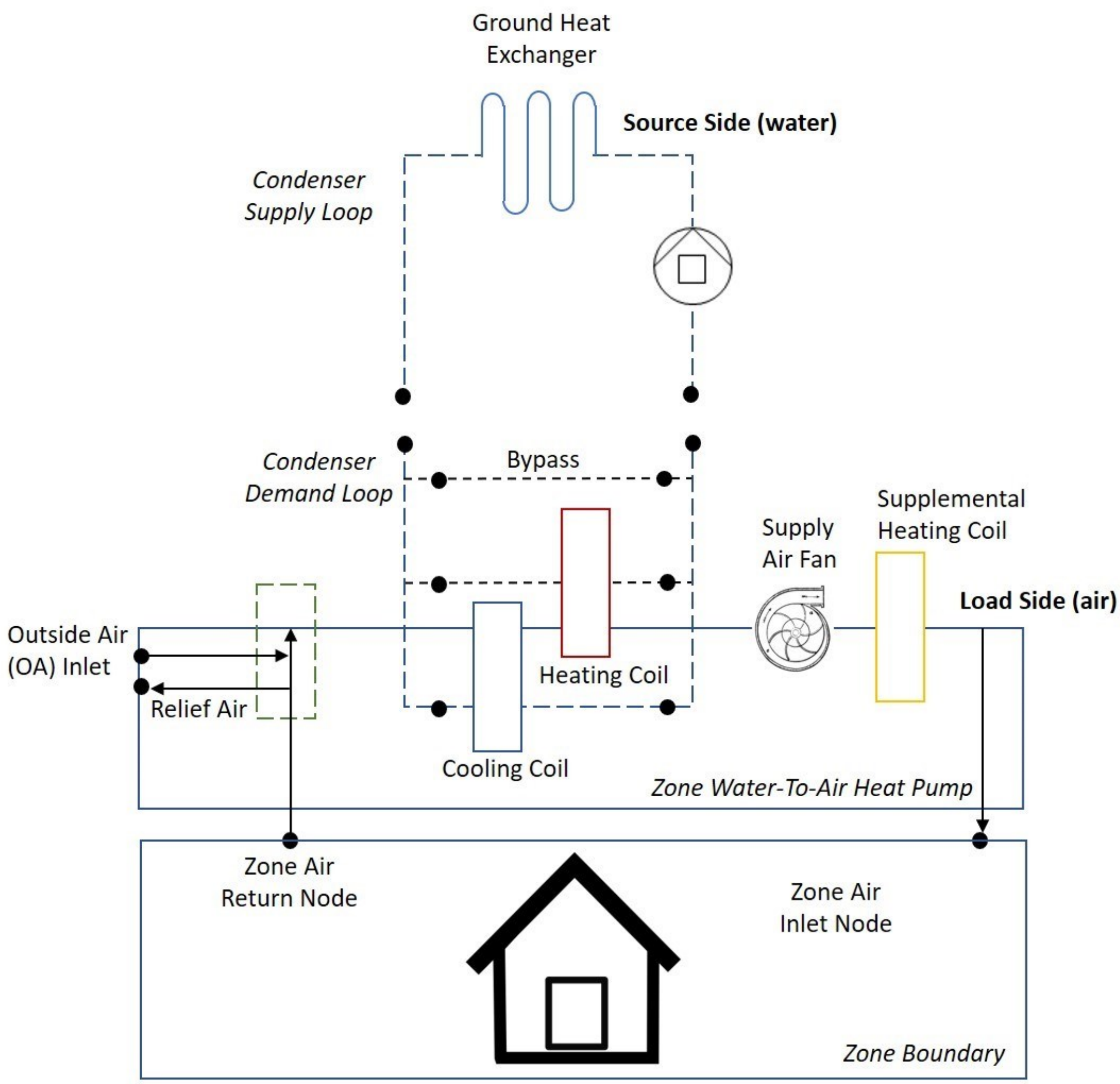


Figure 3.7 Geothermal Heat Pump System Schematic [39]

3.3.3 Building Model Analysis

3.3.3.1 Baseline Energy Use Determination

Determining the baseline energy use for each of the 12 selected cities was the imperative first step to analyzing savings by a geothermal system replacement. Each residential building was simulated with its respective geographical location, weather data, and existing electric cooling and gas heating system. Figure 3.8 shows the baseline meter readings by month and city. Represented in bold lines are the two extremes, the lowest and the highest annual energy use. Duluth, MN had the highest energy use at 40,383 kWh total and Los Angeles, CA had the lowest at 17,855 kWh total. Much relevant information is extracted from this data. The climate regions with cold winters have a significant spike in energy use over the warmer climates during the heating season. This jump is due to reliance on natural gas to fuel the furnace heating system. In the cooling season, an elevated energy use is observed in locations within hot climates, such as Phoenix, AZ.

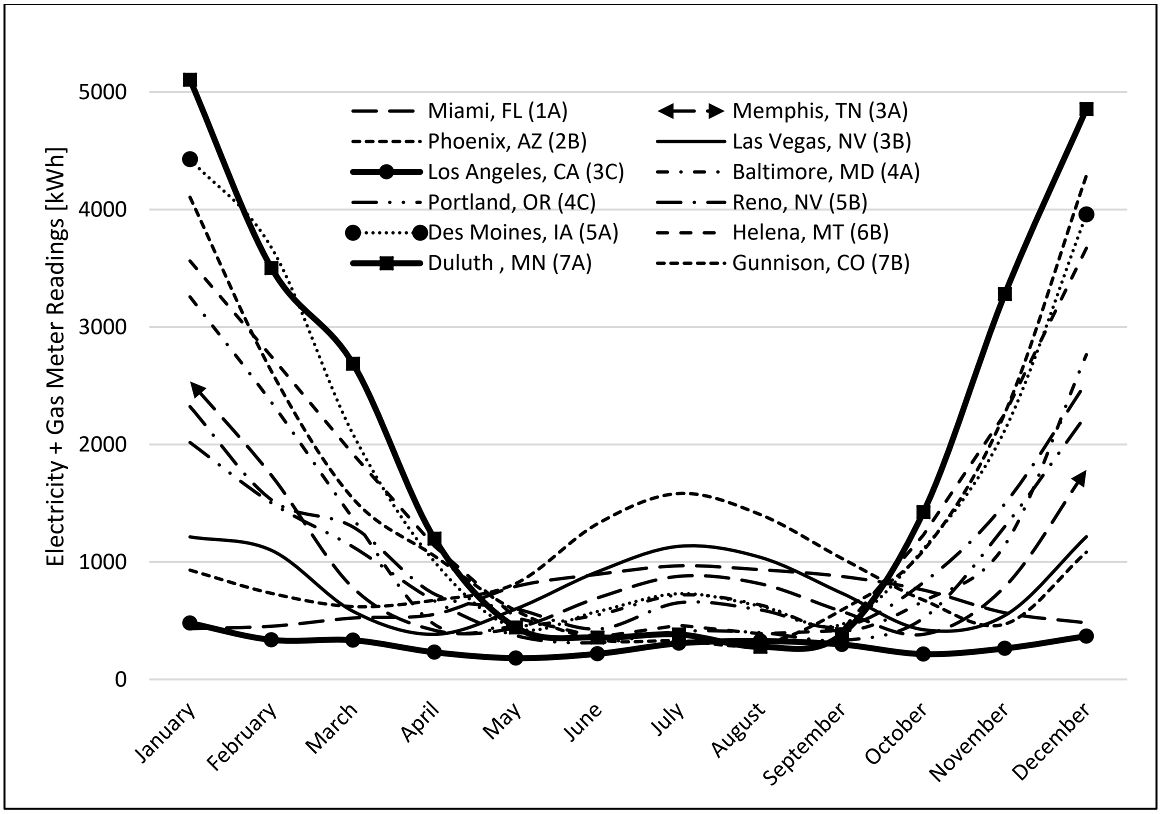


Figure 3.8 Baseline Energy Use Meter Readings by Month and Location

To get a distinct comparison between the energy use in the heating season versus the cooling season, Figure 3.8 was broken down into energy use by electricity and energy use by natural gas in Figure 3.9 and Figure 3.10, respectively. These metrics were graphed on the same axis range to accurately compare to one another. By comparing Figure 3.9 and Figure 3.10 side by side, it is apparent that more energy use is common during the heating season. While variation is still present between the highest and lowest readings in the warm months, the differential is astounding in the cold months. Even the milder climate zones exhibit electricity use equal to or higher than hotter climate zones. These differences can be attributed to a common need for air conditioning in the summer, differences in cooling equipment efficiency, and humidity.

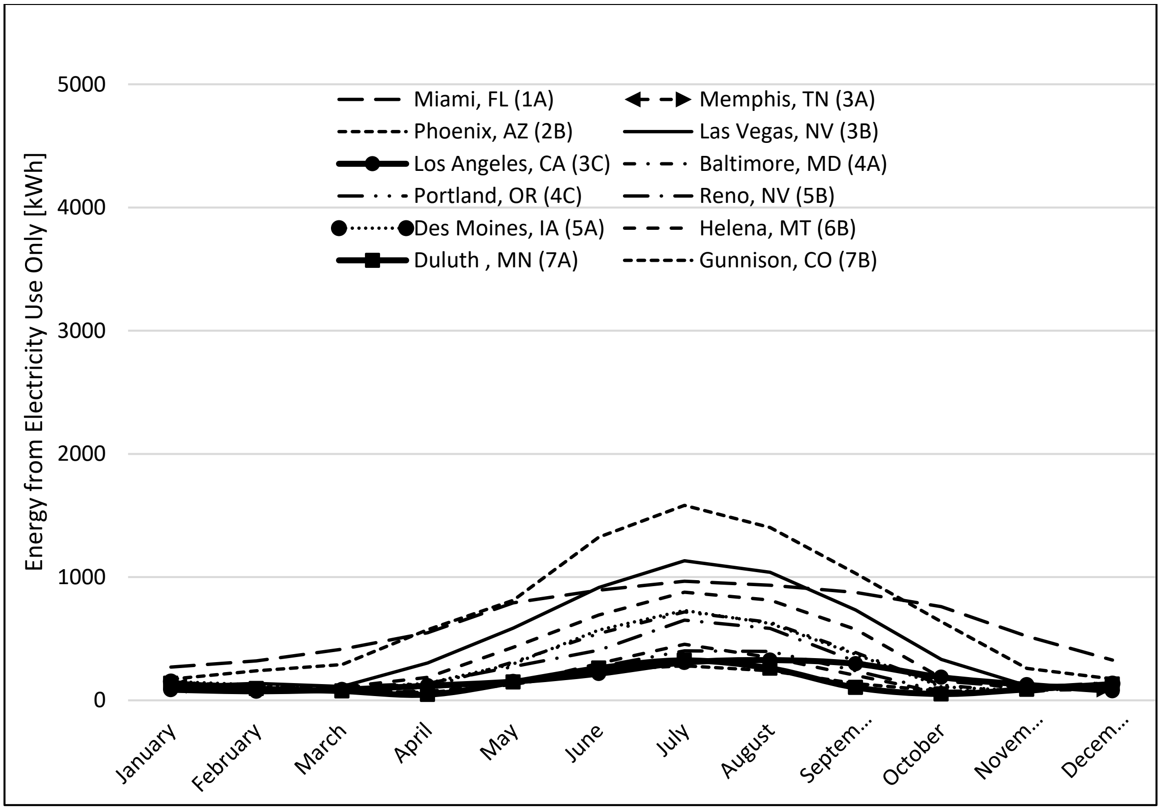


Figure 3.9 Baseline Energy Use from Electricity Only

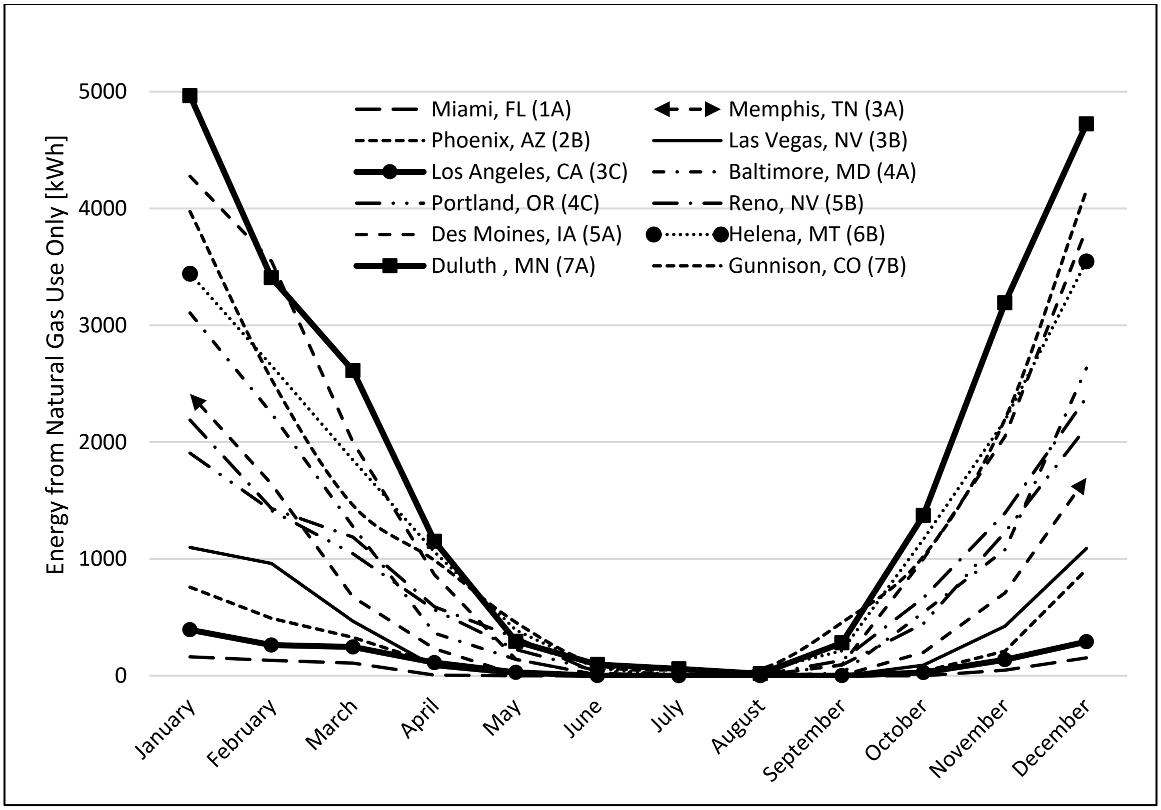


Figure 3.10 Baseline Energy Use from Natural Gas Use Only

Each EnergyPlus™ file was modified to replace the baseline system with the geothermal system. The critical inputs to EnergyPlus™ were the heat pump coefficients, coefficient of performance (COP), borehole length, water flow rate through the heat exchanger, undisturbed ground temperature, and soil thermal conductivity. Other inputs such as grout thermal conductivity, U-tube distance, and pipe thermal conductivity were compiled through previous studies on borefield design optimization [12]. Predominant soil type and water content leads to the determination of thermal conductivity, a key variable for geothermal system design.

3.3.3.2 Area of Interest Determination

All regions shown with the AOI defined were determined with caution and consideration for the climate zone characteristics, as well as available information on soil type, ground heat exchanger design, and availability of prototype home files by EnergyPlus™.

Figure 3.11 illustrates an example of the procedure used to determine the AOI for each of the 12 cities of interest. The interactive Web Soil Survey, provided by the U.S. Department of Agriculture National Resources Conservation service, allows input of a specific address to zoom to and define the AOI [42]. For Miami, FL and the other 11 cities, this method allowed for very geographically specific soil areas defined by the residential homes in Table 3.4. The AOI maps of the remaining cities are given in the Appendix, Figure A.3 through Figure A.13.

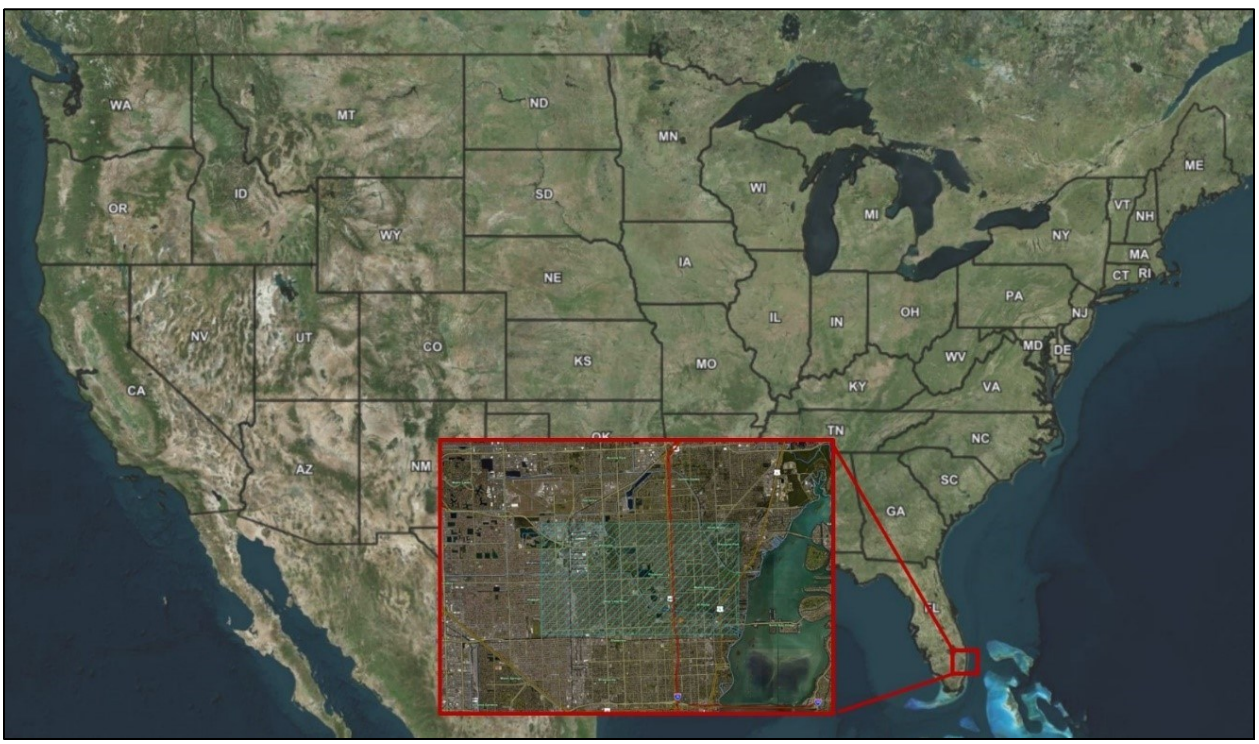


Figure 3.11 Map of Miami, FL Area of Interest

Actual address is Street, Zip Code: NW 82nd Terrace, 33150

The AOI procedure for each location allowed for specific identification of the predominant soil type, water content, and thermal conductivity of the ground beneath the exact address. Table 3.6 summarizes the peak hourly ground load, date of peak, and cooling and heating quadrants each location that will affect the system design capacity and subsequent performance of the geothermal system.

Table 3.6 Ground Loads and Quadrant Classification

Zone	City | State	Peak Hourly Ground Load [W]	Date of Peak	Cooling Quadrant	Heating Quadrant
1A	Miami | FL	8066 W	July 22	Warm / Moist	Warm / Moist
3A	Memphis | TN	6970 W	August 21	Neutral / Moist	Warm / Moist
2B	Phoenix | AZ	9398 W	August 10	Warm / Dry	Warm / Dry
3B	Las Vegas | NV	7392 W	July 5	Warm / Dry	Warm / Dry
3C	Los Angeles | CA	4546 W	September 7	Cool / Moist	Warm / Moist
4A	Baltimore | MD	7242 W	July 9	Cool / Moist	Warm / Moist
4C	Portland | OR	6395 W	July 21	Cool / Moist	Warm / Moist
5A	Des Moines | IA	9581 W	January 23	Cool / Moist	Cold / Moist
5B	Reno | NV	6732 W	July 5	Cool / Dry	Warm / Dry
6B	Helena | MT	8218 W	February 24	Cool / Moist	Cold / Moist
7A	Duluth | MN	9797 W	January 9	Cool / Moist	Cold / Moist
7B	Gunnison | CO	8190 W	December 15	Cool / Dry	Cold / Dry

To clarify the quadrant nomenclature, the cooling and heating quadrants noted in Table 3.6 are rankings relative to one another based on the classification grids in Figure 3.5 and Figure 3.6. For example, Memphis, TN is in the warm / dry heating quadrant. This label does not mean that Memphis has warm winters never inducing a heating load, but rather that the number of HDD is in the lower half of the range of all 12 cities compared. Similarly, Reno, NV is in the cool / dry cooling quadrant. This label does not mean Reno has cool summers never inducing a cooling load, but rather that the number of CDD is in the lower half of the range of all 12 cities. To the contrary, Memphis experiences some very cold winter days, and Reno logs very warm summer days in the weather records. An interesting observation is the date of the highest ground load. Ground load represents the maximum heat either rejected to the ground to achieve cooling setpoint or the heat absorbed from the ground to achieve heating setpoint. Climate zones 1 through 4 and 5B have a peak ground load in the cooling months of July through September. However, climate zones 5A, 6 and 7 have a peak ground load in the heating season, indicating a higher peak heating demand annually than cooling demand.

3.3.4 Incentive and Payback Analysis

3.3.4.1 Incentive Analysis

A major focus of this investigation is the consideration of all federal and local financial incentives available to residential building owners in each climate zone. While all states quality for the federal Residential Renewable Energy Tax Credit, many other local incentives are available to mitigate the high initial capital investment cost of installing a GHP system. Table 3.7 itemizes the additional local incentives present in each of the 12 selected cities, compiled through the Clean Energy Technology Center Database of State Incentives for Renewables & Efficiency (DSIRE) [28].

Table 3.7 Incentives by Location

	Program	Incentive
Federal (All)	Residential Renewable Energy Tax Credit	Tax credit equal to 30% of investment
Los Angeles, CA	N/A	
Miami, FL	Property Tax Abatement for Renewable Energy Property	Florida provides a 100% property tax exemption (1.12%) for residential renewable energy property
Las Vegas, NV	N/A	
Portland, OR	Renewable Energy Systems Exemption	100% Property Tax Incentive (1.125%)
	Portland General Electric - Residential Energy Efficiency Rebate Program	Heat Pump Instant Discount: $200; Efficient Heat Pumps: $700
Memphis, TN	TVA Partner Utilities - eScore Program	Geothermal Heat Pump: $250/Unit
Phoenix, AZ	Energy Equipment Property Tax Exemption	100% of increased value (0.802%)
Gunnison, CO	Gunnison County Electric - Residential Energy Efficiency Rebate Program	Geothermal Heat Pump: $500/ton plus $150/unit
Reno, NV	N/A	
Baltimore, MD	Residential Clean Energy Grant Program	New GHC: $3,000/project
	Baltimore Gas & Electric Company (Gas) - Residential Energy Efficiency Rebate Program	Geothermal Heat Pump: $1,500
Des Moines, IA	Geothermal Heat Pump Tax Credit	20% of the Federal Tax Credit, equivalent to 6% of the system cost
Helena, MT	Residential Alternative Energy System Tax Credit	$500 per individual taxpayer; up to $1,000 per household.
	Residential Geothermal Systems Credit	$1,500
	Renewable Energy Systems Exemption	100% for 10 years (0.957%)
Duluth, MN	Minnesota Power - Residential Energy Efficiency Rebate Program	Ground Source Heat Pump: $100-$200 per ton plus $200 for ECM motor

Some of the incentives are county-specific, so they may not be applicable to all cities in the climate zone represented by the selected city. For cities that have a property tax exemption incentive, the property tax rate is stated in the respective row in Table 3.7 [74].

3.3.4.2 Payback Analysis

Two methods of calculating payback period were executed in this study, with the purpose of demonstrating the variability in the data depending on the method. The discounted payback period (DPP) accounts for the expected inflation rate over the lifetime of the system, as well as discount rate. The actual payback period (APP) uses average annual utility cost increases to modify annual savings [75]. While several other methods exist, the DPP and APP methods are valid and effectively demonstrate the method-dependent payback sensitivity.

3.3.4.2.1 Discounted Payback Period

Payback period analysis was first performed using the DPP method. The combination of optimal system size, annual monetary savings, and available incentives were considered to calculate the payback period for each climate-specific prototype home. This method accounts for discount rate and inflation. To translate energy savings into monetary savings, the price of electricity for each location is shown in Table 3.8.

Table 3.8 Electricity Prices by State current October 2019 [76]

Zone	City | State	Utility Cost [$/kWh]
1A	Miami | FL	0.1161
2B	Phoenix | AZ	0.1284
3A	Memphis | TN	0.1067
3B	Las Vegas | NV	0.1186
3C	Los Angeles | CA	0.1890
4A	Baltimore | MD	0.1333
4C	Portland | OR	0.1092
5A	Des Moines | IA	0.1267
5B	Reno | NV	0.1186
6B	Helena | MT	0.1118
7A	Duluth | MN	0.1338
7B	Gunnison | CO	0.1214

Electricity Local, "Local Electricity Rates and Statistics," *Electricity Rates & Usage*, 2019. [Online]. Available: https://www.electricitylocal.com/. [Accessed: 25-Feb-2020].

Using the annual savings value, Equation 3.1 calculates $Cost_n$, the dollar amount left on an investment after year n. This value is dependent upon the discount rate, j, and the inflation rate, i. With the variables, the remaining deficit at the end of each year is determined.:

$$Cost_n = \frac{AS}{[(1+j)/(1+i)]^n} \tag{3.1}$$

The value used in this study for inflation rate is i = 2.44% and the current discount rate is j = 3.0%, based on the Federal Energy Management Program's (FEMP) most recent publication [51]. While j = 3.0% is used in this study, the Office of Management and Budget (OMB) Circular A-94 advises payback analyses be performed using the current discount rate as well as the historical average discount rate of j = 7.0% [52] [53]. The discount rate is a factor of notable sensitivity to the payback period, as shown in Neves et al. [56], in which both discount rates were used and results compared. It should be noted that the discount rate used in a financial analysis of this type will influence the outcome and is a good candidate for sensitivity analysis. Table 3.9 is a summary of parameters for the financial investigation.

Table 3.9 Definition of Variables Used in Climate Zone Payback Analysis

Variable	Parameter	Units
$Cost_{cb}$	Initial Cost Before Incentives	[$]
Cap_{HP}	Heat Pump Cooling Capacity	[tons]
in_i	Incentive i Savings	[$]
$Cost_{ca}$	Initial Cost After Incentives	[$]
AS	Annual Savings	[$]
$Cost_e$	Electricity Cost	[$/kWh]
j	Discount Rate	[%]
i	Inflation Rate	[%]
n	Year Post-Investment	[year]
$Cost_n$	Investment Deficit Remaining after Year n	[$]
DPP	Discounted Payback Period	[years]
APP	Actual Payback Period	[years]
Lifetime Net	Total System Lifetime Savings	[$]

Initial cost before incentives, $Cost_{cb}$ will vary for each climate zone based upon the heat pump size that achieves the maximum energy savings from simulation results [74]. The installation cost per ton of cooling used in this study is $4,000 [1]. Therefore, $Cost_{cb}$ is calculated using Equation 3.2:

$$Cost_{cb} = (\$4{,}000)Cap_{HP} \tag{3.2}$$

The initial cost after incentives is shown in Equation 3.3:

$$Cost_{ca} = Cost_{cb} - \sum_{i=1}^{n} in_i \tag{3.3}$$

In addition to payback period, or the duration necessary to make up the initial capital investment based on annual energy savings, a total system lifetime net value can be determined. For the geothermal heat pump system, a system lifetime is 25 years.

$$Lifetime\ Net_{DPP} = -Cost_{ca} + (25years)AS \tag{3.4}$$

3.3.4.2.2 Actual Payback Method

Actual payback method data accounts for the consistently rising cost of energy in the residential sector. Choosing the rate of energy cost increase is a critical component to the results. The APP method was described by Hanna [75] in the Journal of Consumer Affairs several decades ago. The annual cost increase at that time was 8%, a value seeming quite radical for the current economy. More recent data was reported in a 2016 update by Sandoval [77]. The publication follows the residential cost of energy per kWh over a 14-year time period between 2001 and 2014. This cost increase is 67% in 14 years. Averaging across the time period results in 5.15% energy cost increase per kWh per year. This is the value used in this report for calculating the APP. The APP method is quite simple. The initial annual savings in year $n = 1$ is increased by 5.15% each year. That new annual savings is subtracted from the remaining balance left on the capital investment. For example, if annual savings for an energy efficiency project is $100 in year n = 1, the following year the annual savings will be increased as in Equation 3.5:

$$AS_n = 1.0515(AS_{n-1}) \tag{3.5}$$

where $n = 2$ through $n = 25$, the year the system is expected to reach the end of its useful life. From the iterated annual savings values, the APP and system lifetime savings can be determined. Using the APP method, Equation 3.4 is modified to Equation 3.6 below:

$$Lifetime\ Net_{APP} = -Cost_{ca} + \sum_{n=1}^{n=25} AS_n \tag{3.6}$$

Two metrics of payback period and system lifetime net savings will provide excellent data points to classify certain climate zones as viable or not viable for geothermal space heating and cooling technology. Significant differences may result in the DPP and APP methods, but a consumer will be presented with all the data, sensitivities, risks, and benefits.

3.4 Results and Discussion

3.4.1 Energy Savings Analysis

A summary of all cities and all heat pump capacity results are displayed in Figure 3.12. The savings percentage was calculated by comparing the HVAC system meter reading from the geothermal system to the HVAC system meter reading from the baseline home. The percentages reported reflect annual savings in energy consumption. The HVAC system meter reading for the baseline home includes cooling electricity, natural gas heating, and fans. The same system meter reading for the alternative system home include cooling electricity, heating electricity, fans and ground water circulation pump. As can been seen, climate zones 3 through 7 have satisfying results, and climate zones 1 and 2 experience low savings numbers needing further investigation.

The utility cost in each location is a critical variable in the analysis of system feasibility. Of note, the two climate zones that result in negative savings are the two cities that had the highest peak ground load in Table 3.6. In fact, Miami, FL and Phoenix, AZ were the only two cities that exceed a peak ground load of 8,000 W cooling.

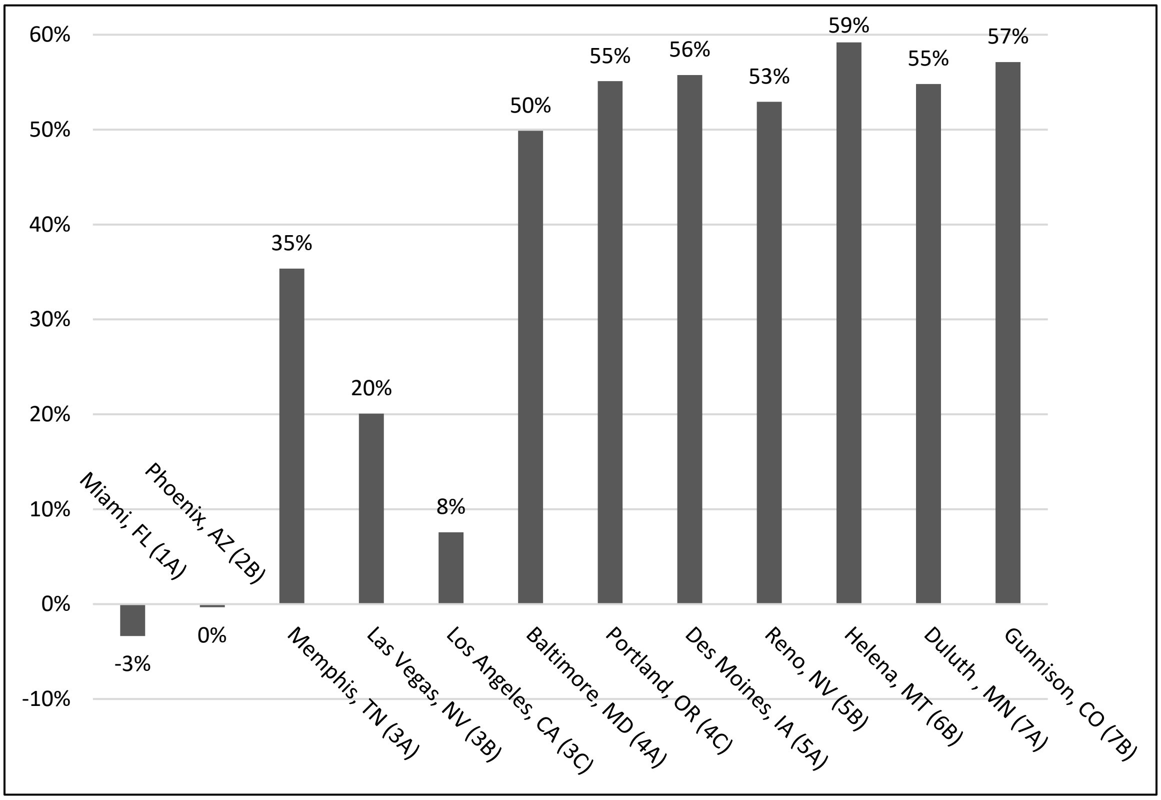


Figure 3.12 Savings by Climate Zone

The greatest savings of 59% is in Helena, MT and the lowest savings is -3% in Miami, FL. The diverse results are due to the weather data, heating or cooling demand magnitudes and durations, and borefield calculations based on local conditions. To further analyze the energy use comparison, Figure 3.13 breaks the total consumption into components of cooling electricity, heating electricity, heating gas, pumps, and fans. For all climate zone, heating electricity is zero for the baseline system, and heating gas consumption is zero for the alternative geothermal system. Pump electricity represents the consumption of the ground loop water circulating pump.

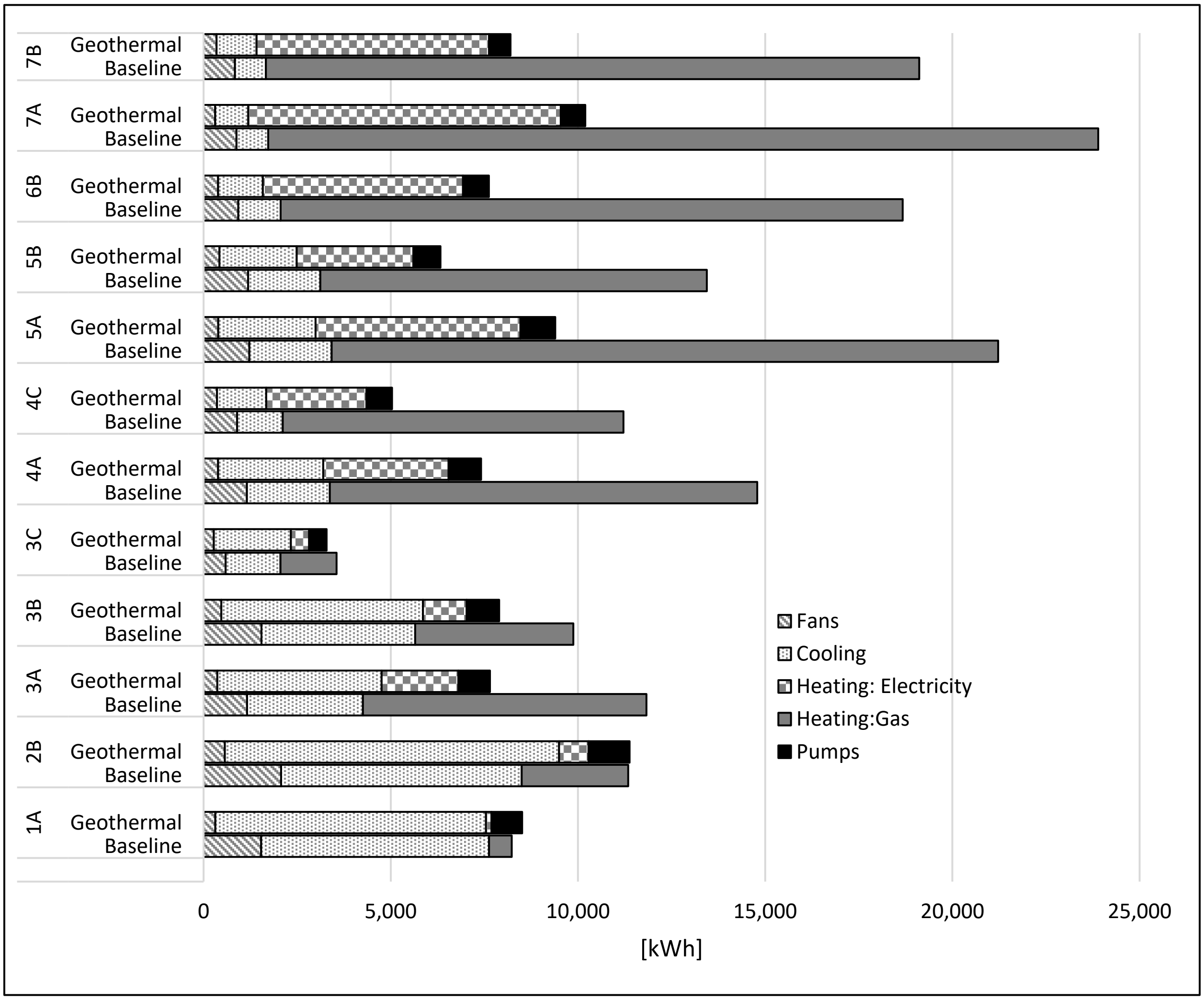


Figure 3.13 Energy Comparison by Component

From this itemized comparison in Figure 3.13, it is easy to see the source of the immense savings in the heating-dominant climates is from the elimination of natural gas heating. However, this energy source is replaced with heat pump electricity in the heating season, and the introduction of electricity use from the ground loop water circulating pump. Electricity consumption to cool has an increased demand for climate zones across the United States. In climate zone 7B, which has the highest savings, the supplemental electric heating coil accounted for 10.5% of the total power consumed for heating electricity. This metric is significant and can raise caution as a system performance indicator. If the supplemental electric heating coil operates excessively, then the heat pump is not performing as desired and the geothermal energy source is ineffective at reaching air comfort requirements. Results in Figure 3.13 indicate that a geothermal system will yield cost savings only in climates that have at least a minimal heating load throughout the calendar year.

While Figure 3.12 shows savings percentage, a different perspective of the energy consumption delta is essential to the financial analysis. Two climate zone representative cities may have identical savings percentages, but vastly different [kWh] savings. Figure 3.14 demonstrates this distinction. In Gunnison, CO the savings exceeds 2,500 kWh in December. In Los Angeles, CA the savings is approximately 200 kWh. These two results demonstrate the range in [kWh] savings even though both cities save nearly 50% in December.

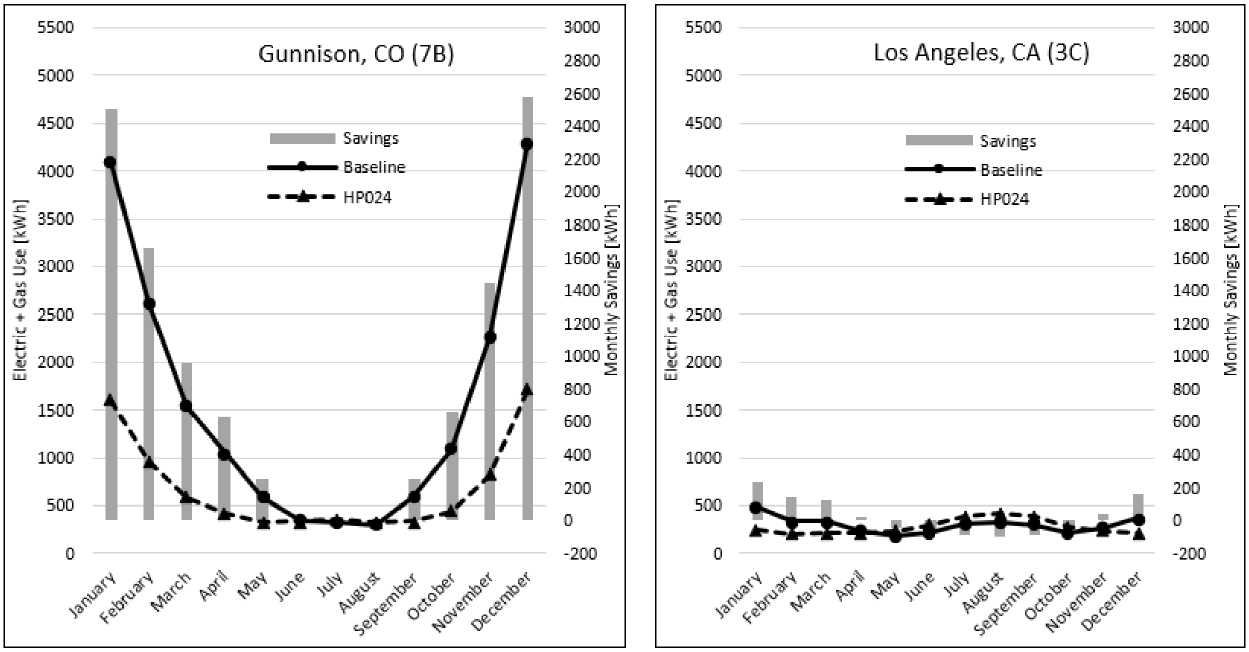


Figure 3.14 Energy Consumption Magnitude Comparison

Each simulation resulted in EnergyPlus™ outputs reporting monthly, daily, and hourly energy consumption by HVAC component. The program was called to autosize the design system capacity based on the regional weather data, home characteristics, and soil and borehole properties inputs. Figure 3.14 provides a sample of the consumption profiles generated for each city. From this profile, the annual energy savings was determined. Table 3.10 displays the tabular view of the data shown graphically in Figure 3.12. Reported are percentage savings for each location, EnergyPlus™ recommended design capacity, and resulting cost before incentives for system installation, $Cost_{cb}$ [1].

Table 3.10 Annual Savings and Capital Investment

Zone | City, State	**Annual Energy Savings [%]**	**Design Capacity [*Btu/hr*]**	***Cost$_{cb}$* [$]**
1A | Miami, FL	(3%)	34,200	$ 12,000
2B | Phoenix, AZ	0%	43,800	$ 12,000
3A | Memphis, TN	35%	33,960	$ 12,000
3B | Las Vegas, NV	20%	35,640	$ 12,000
3C | Los Angeles, CA	8%	23,040	$ 8,000
4A | Baltimore, MD	50%	35,160	$ 12,000
4C | Portland, OR	55%	29,520	$ 12,000
5A | Des Moines, IA	56%	36,360	$ 12,000
5B | Reno, NV	53%	30,600	$ 12,000
6B | Helena, MT	59%	28,200	$ 12,000
7A | Duluth, MN	55%	27,720	$ 12,000
7B | Gunnison, CO	57%	24,000	$ 8,000

A note about sensitivity is prudent. Reviewing the savings results from Figure 3.12 highlight an oddity, at first glance, between Las Vegas, NV and Phoenix, AZ. Both considered to be hot, desert climates in close geographic proximity to one another, why will such similar cities yield a $20\% - (0\%) = 20\%$ difference in savings? This disparity needed additional investigation. The extreme summers were the focus. Figure 3.15 displays the average annual daily high and low temperatures in both cities from June 1 through August 31. As shown, Phoenix high and low temperatures are both above those of Las Vegas. While the difference may seem minimal, from 2°F to 6°F, the cumulative difference seems to have a significant impact on the GSHP performance. Additionally, the ground temperatures are 69°F and 73°F in Las Vegas and Phoenix, respectively. The higher ground temperature in Phoenix means a lesser delta between the heat sink and the water exiting the heat pump to reject heat to the ground. While this delta is considered in sizing the borehole length, these results are calculated from the optimal borehole length with all variables considered [35].

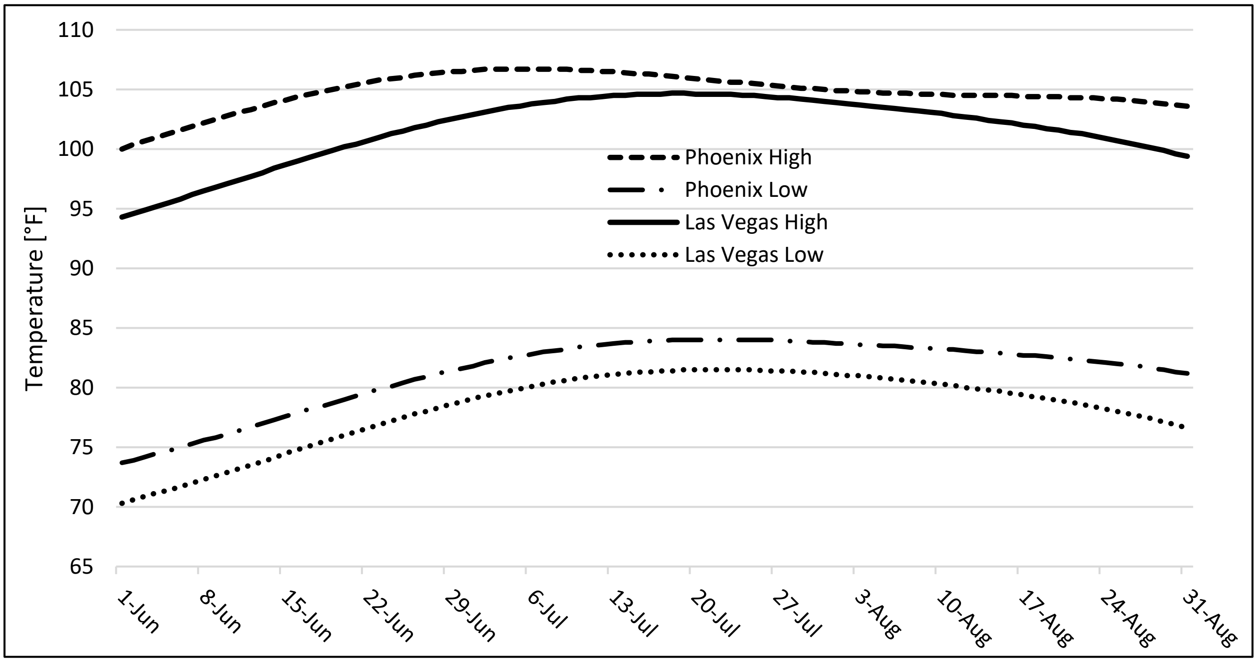


Figure 3.15 Temperature Sensitivity Analysis

Comfort setpoint was also a curious factor. For a low savings city, Phoenix, AZ, a sidebar analysis was performed on the effect of varying cooling setpoint temperature. The results in Figure 3.12 resulted from a cooling setpoint of 75°F in the cooling months. By increasing the setpoint by 1°F up to 78°F, the savings profile experienced notable changes. The 78°F maximum value was chosen per recommendations in the ENERGY STAR Guide to Energy-Efficient Heating and Cooling, which actually recommends 78°F be the minimum value to be increased by homeowner comfort [78]. Figure 3.16 shows the setpoint analysis outcome.

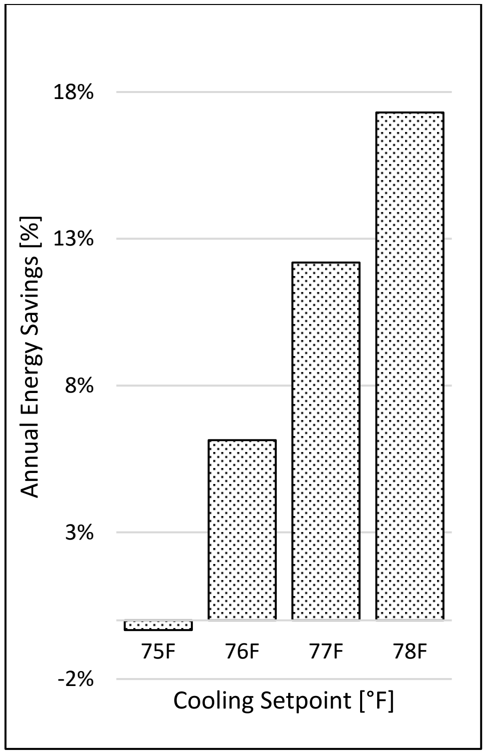


Figure 3.16 Setpoint Sensitivity Analysis

While Figure 3.16 is for only one city, residences in all climate zones with high cooling demand will experience similar fluctuations to user cooling setpoints. Clearly, cooling energy consumption powerfully dictates potential savings. The setpoint variable is controllable by the end user, while the temperature profile and ground temperatures are not. However, all three are noteworthy in the energy savings discussion.

3.4.2 Payback Period Analysis

Two metrics highly important to the homeowner are the initial capital investment and the payback period. Table 3.11 presents the local utility cost per kWh, and ultimate annual monetary savings for each climate zone [79]. The annual energy savings was calculated by the summation of the monthly savings for each city. By multiplying the annual energy savings by the utility cost per kWh for each city, annual monetary savings is determined.

Table 3.11 Utility Data and Savings Analysis

Zone	City | State	Utility Cost [$/kWh]	Annual Consumption Savings [kWh]	Annual Monetary Savings [$]
1A	Miami | FL	0.1161	(277)	$ (32)
2B	Phoenix | AZ	0.1284	(38)	$ (5)
3A	Memphis | TN	0.1067	4,183	$ 446
3B	Las Vegas | NV	0.1186	1,983	$ 235
3C	Los Angeles | CA	0.1890	269	$ 51
4A	Baltimore | MD	0.1333	7,376	$ 983
4C	Portland | OR	0.1092	6,178	$ 675
5A	Des Moines | IA	0.1267	11,830	$ 1,499
5B	Reno | NV	0.1186	7,116	$ 844
6B	Helena | MT	0.1118	11,052	$ 1,236
7A	Duluth | MN	0.1338	13,071	$ 1,833
7B	Gunnison | CO	0.1214	10,917	$ 1,325

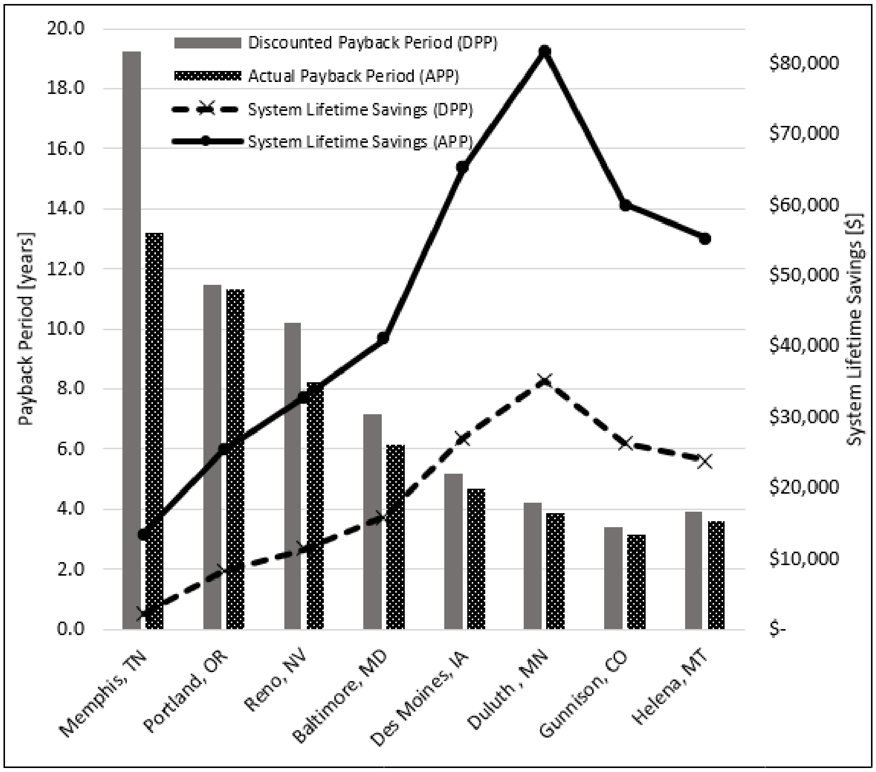
Values range from $(32) in Miami, FL to $1,833 in Duluth, MN. With this data, the homeowner can focus on the financial forecast resulting from replacing an existing system with geothermal.

However, even significant annual monetary savings may not be enough incentive to implement a change in technology. A savvy customer will want to know the payback period for a fully informed decision. Equation 3.3 calculated the total capital investment with all incentives available per city, shown in Table 3.7. The total capital investment results with incentive values are reported in Table 3.12. Values range from the lowest in Gunnison, CO of $4,450 to $8,400 in Phoenix, AZ and Reno, NV. Recall, the capital investment without incentives considered was a function of the heat pump size that matched the design capacity by EnergyPlus™ autosize calculations.

Table 3.12 Investment and Incentive Analysis

City | State	Total Capital Investment Without Incentives	Federal Tax Credit	Other Local Incentives Discount	Total Capital Investment With Incentives
Miami | FL	$12,000.00	$3,600.00	$134.40	**$8,265.60**
Phoenix | AZ	$12,000.00	$4,800.00	$96.24	**$8,303.76**
Memphis | TN	$12,000.00	$3,600.00	$250.00	**$8,150.00**
Las Vegas | NV	$12,000.00	$3,600.00	$0.00	**$8,400.00**
Los Angeles | CA	$8,000.00	$2,400.00	$0.00	**$5,600.00**
Baltimore | MD	$12,000.00	$3,600.00	$1,500.00	**$6,900.00**
Portland | OR	$12,000.00	$3,600.00	$900.00	**$7,500.00**
Reno | NV	$12,000.00	$3,600.00	$0.00	**$8,400.00**
Des Moines | IA	$12,000.00	$3,600.00	$720.00	**$7,680.00**
Helena | MT	$12,000.00	$3,600.00	$3,648.40	**$4,751.60**
Duluth | MN	$12,000.00	$3,600.00	$800.00	**$7,600.00**
Gunnison | CO	$8,000.00	$2,400.00	$1,150.00	**$4,450.00**

Discounted payback period, actual payback period, and system lifetime savings using each method are calculated for each climate zone using Equations 3.1 through 3.6. System savings lifetime is the reported net savings at the end of the system's useful life, assumed at 25 years. Both values are shown in Figure 3.17.



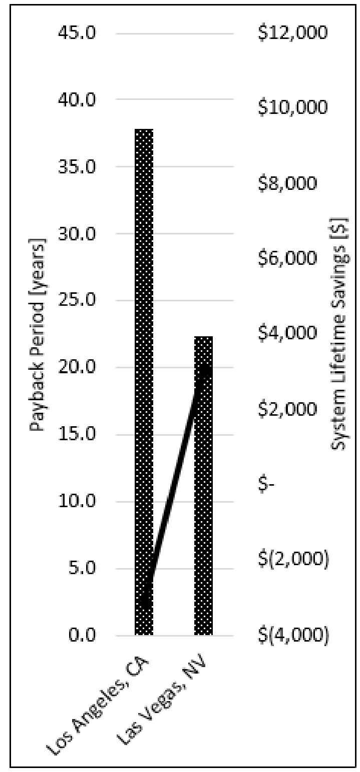


Figure 3.17 Viable Payback Cities (A) and High Payback Cities (B)

The climate zones represented in Figure 3.17 required plotting on two separate scales due to the great variance of the results. Figure 3.17A shows the payback period of 8 of the 12 cities. Figure 3.17B shows the results from the remaining 2 cities with positive savings results but payback as high as 38 years. The data was obscured by placing these extremes on the same graph. As can be seen, Figure 3.17B only displays results for the APP, not the DPP, because the payback period was so high in these locations that it exceeded the system lifetime and distorted the scale unnecessarily.

The cities that had no local incentives to augment the federal incentive are Los Angeles, CA and Las Vegas and Reno, NV. Interestingly, Los Angeles and Las Vegas have the two highest payback periods at 37.8 years (APP) and 22.3 years (APP), respectively. This observation highlights the influence of local incentives on payback period of certain climate regions. However, the absence of state incentives did not cause Reno, NV to have an unacceptable payback due likely due to a larger heating load. The shortest payback period is 3.2 years (APP) in Helena, MT. The system lifetime savings value is an influential metric. In climate zone 7A, the representative city of Duluth, MN anticipates a net monetary savings of over $81,000. Whether the data is compelling enough homeowners to embark on this technology change is now a consumer choice.

3.5 Chapter Summary and Conclusion

The goal of this study is to identify climate zones within the continental United States that are viable candidates for geothermal space heating and cooling technology, considering energy savings and payback period. Energy savings ranged from 59% annually in Helena, MT to -3% in Miami, FL. By analyzing trends in Figure 3.12, most cities and climate zones experienced significant energy consumption savings. Payoff periods range from 3.2 years in Duluth, MN up to 37.8 years in Los Angeles, CA. Once the knowledge is available, labeling good climate zone candidates for geothermal space heating and cooling is possible. However, classifying viable versus nonviable is a subjective matter, because the acceptable payback period will vary amongst the owners of residential buildings. To have quantitative criteria, this study used the results of the consumer survey in Karytsas [15] as categories. Uniting the information in the survey and the payback period data determined for the 12 climate zones in the United States, the results are concluded in Table 3.13.

Table 3.13 Percentage of Residents Willing to Accept Payback Period

Climate Zone	Representative City	Payback Period [years]	Viable	Nonviable
1A	Miami, FL	N/A	N/A	N/A
2B	Phoenix, AZ	N/A	N/A	N/A
3A	Memphis, TN	13.2	7.4%	92.6%
3B	Las Vegas, NV	22.3	5.0%	95.0%
3C	Los Angeles, CA	37.8	5.0%	95.0%
4A	Baltimore, MD	6.1	32.5%	67.5%
4C	Portland, OR	11.3	19.1%	80.9%
5A	Des Moines, IA	4.7	100%	0%
5B	Reno, NV	8.2	19.1%	80.9%
6B	Helena, MT	3.6	100%	0%
7A	Duluth, MN	3.9	100%	0%
7B	Gunnison, CO	3.2	100%	0%

Using this classification scheme, between 5.0% and 100% of homeowners are willing to accept the payback period, depending on the climate zone. Let it be noted that the actual payback period (APP) was the data set used to make the classification. For climate zones 1A through 5B, the high percentages in the nonviable column do not show promise for widespread replacement of traditional HVAC system with GSHP systems. The substantial initial cost seems the major barrier, now made quantifiable with data in this study. Lack of knowledge, fear of the unknown, and resistance to change are a sampling of the qualitative barriers to increased adoption.

In reference to initial cost, an interesting discovery emerges from the data results. Montana and Colorado have implemented robust local incentive programs, as seen in Table 3.7. In contrast, Nevada has no additional incentives above the federal tax credit. Without coincidence, it is the two climate zones in Montana and Colorado that prove two of the three shortest payback periods. Therefore, in addition to the utility cost per city, heat pump size, or soil characteristics, a noteworthy factor is the presence or absence of local incentive programs. These additional financial offers further minimize initial capital investment through rebates and credits, as well as annual savings through property tax deductions.

From the data presented, certain steps may be taken to achieve even more accurate climate zone payback data, and to gather public interest. Knowledge is the critical tool to educated decisions. The climate zone specific knowledge presented aims to educate the residential sector on accurate expectations for implementation of geothermal heat pump technology.

CHAPTER IV

PHOTOVOLTAIC (PV) COMPLEMENTARY SYSTEM AND THE ROAD TO NET ZERO ENERGY BUILDINGS

Homeowners across the globe are continually seeking methods of improving energy efficiency for financial benefit and personal satisfaction. From small contributions such as swapping light bulbs to large capital investment initiatives like upgraded heating and cooling systems, homeowner decisions require accurate data and confidence in potential outcomes. This study models the path to net-zero energy for two separate HVAC + PV systems in residential buildings across 12 Unites States climate zones, and determines the optimal combination for each climate zone. An existing, traditional air-conditioning system with natural gas furnace is paired with a PV array. The net-zero results are compared to the same residence upgraded to a climate-customized geothermal heat pump HVAC system paired with a PV array. Results confidently favor the geothermal HVAC system + PV for climates with a significant heating demand in winter, and the baseline + PV system proves financially preferred for cooling-dominant climates. This research delivers climate-specific recommendations for the preferred net-zero HVAC + PV system through analysis of accurate energy performance and financial forecasting. Recommendations provide homeowners with valuable expectations on two HVAC + PV options along the path to a net-zero energy home.

4.1 Net Zero Energy (NZE) Introduction

Renewable energy technologies exhibit varying performance success across U.S. climates. Geothermal technology may be preferred in one location and less effective in another. The variability can be due to climate conditions, soil characteristics, and home construction features. In geothermal viable climates, installation of a geothermal heat pump (GHP) for space heating and cooling can be an effective energy efficiency improvement, saving significant and energy and dollars annually. This study compares homes with a baseline HVAC system with the same home retrofit with a GHP HVAC system. Each is paired with a solar photovoltaic (PV) array for on-site energy generation. The baseline system consists of a traditional, direct expansion (DX) cooling system and natural gas furnace heating system. The GHP system is a climate-customized ground source heat pump and geothermal borefield.

Prior literature has compared different HVAC + PV systems to compare alternatives for energy use. Wu and Skye [80] analyzed energy use by an air-source heat pump (ASHP) + PV array to that of geothermal heat pump (GHP) + PV array. Results revealed that the optimal HVAC + PV combination consists of the GHP in climates with a moderate to high heating demand. However, the GHP system often used more energy than the ASHP in warm climates. This study builds on the CHAPTER III investigation that focused on energy and financial outcomes of a GHP HVAC system across 12 climate zones in the United States. Adding to the previous study, the path to net-zero energy is investigated by adding the PV array and comparing performance to the baseline system + PV combination.

Defining the term net zero energy (NZE) is an imperative first step to developing a design intent and strategy for residential dwellings. A catchy phrase in recent years to all building owners, the NZE concept may be misunderstood unless clear parameters are set forth for particular projects.

Torcellini et al. [81] presented a concise set of definition and design intentions for various buildings and site situations at the American Society for an Energy-Efficient Economy Summer Study. Breaking the term down into components, “net zero” commonly means the incoming plus outgoing equals zero. In the context of energy, the incoming energy is the energy required by the building for daily functioning, and the outgoing energy is the energy generated by renewable sources. “Energy” in NZE means the required capacity from all sources, including all fuels and electricity, such that a residential building owner can comfortably heat and cool, operate all appliances, cooking ranges, lighting, and enjoy consistent domestic hot water heating. Within this context, the definition of NZE can be more clearly delineated for a residential building. Torcellini et al. [81] defines four variations of NZE: (1) Net Zero Site Energy Building, (2) Net Zero Source Energy Building, (3) Net Zero Energy Cost Building, and (4) Net Zero Energy Emissions Building. The four variations differ in the interpretations of energy consumption, location of energy generation, economics attached to consumption, and pollutants attributed to processing. For this study, the first definition for a net zero site energy building (NZSEB) is applied to residential homes across the United States climate zones. Two scenarios are compared for NZE potential. The first is a PV system alone, where the baseline home consisting of a traditional DX cooling and gas furnace HVAC system is augmented with a PV array. The second is a GHP + PV combination system, adding the PV array to the home already retrofit with the climate-customized geothermal heat pump HVAC system in CHAPTER III.

4.2 Materials and Methods

4.2.1 Assumptions

Building upon the definition of NZSEB requires stated assumptions for this application. As [81] profoundly reminded designers, the initial goal of all NZE projects is to achieve energy efficiency. It would not make sense to invest large sums of money to generate energy equal to consumption if the building is full of outdated, inefficient equipment, appliances, lighting, construction, and beyond. This effort would proverbially be throwing money out the single-pane window. With this initial goal in mind, the following assumptions are in effect for the NZE investigation in this study:

1) Renewable energy source is photovoltaic (PV) array that resides on-site and supplies energy to the residential building only.
2) NZE analysis includes energy required for the entire facility electricity and gas demand. However, it should be noted that the only energy-efficiency upgrades have been performed on the HVAC system are those described in CHAPTER III by installation of a GHP system.
3) PV capacity is sized to either achieve NZE for the building or 12 kW, whichever is lower. The 12 kW value is the maximum array capacity for the BEopt™ simulation engine used in this study.
4) NZE measure is for consumption and generation, not cost. The historical and predicted variability of energy prices makes a zero-cost building challenging to guarantee. PV capacity (array size) is sized to offset energy use only.
5) Results reflect net metering analysis, wherein consumption is reduced by the generation, and excess energy may be sold back to the grid. Each location varies in net metering rates and compensation.

4.2.2 Existing Data

A previous study analyzing residential, climate-customized geothermal heat pump space heating and cooling performance [82] was the inspiration for this follow-on investigation. The presented data reported the energy performance and financial forecast for the GHP system in 12 diverse climate zones across the United States. Energy use with the GHP system was compared to the energy use with a baseline home consisting of DX electric cooling and natural gas furnace heating. Annual energy performance data from the baseline home and the GHP-retrofit home are used in this study for the facility energy demand. Moving forward to the NZE analysis commences where the GHP retrofit concluded.

4.2.3 Modeling and Simulation

Energy consumption data for the baseline HVAC home was tabulated through EnergyPlus™, the Department of Energy whole building simulation engine. Energy consumption data for the GHP HVAC system home was carried in from CHAPTER III. Table 4.1 outlines the method used to add a PV array to homes in the 12 climate zones.

Table 4.1 Procedure for Net-Zero System Investigation

Step	Activity
1	Retrieve facility energy consumption for homes with GHP system in each climate zone
2	Input home characteristics, weather file, PV azimuth and tilt into BEopt™
3	Run optimization simulation for 0.5kW to 12kW PV arrays
4	Choose PV array size that generates the energy equal to the annual consumption from Step 1
5	Record cost [$/W] of chosen PV array size, as provided by BEopt™
6	Determine local incentives for geothermal plus solar photovoltaics
7	Calculate capital investment for combined system after incentives are applied
8	Calculate payback period and system lifetime savings for combined system
9	Compare combined system to geothermal system for best choice per climate zone

For the baseline + PV system, the annual energy consumption includes HVAC plus all other facility components requiring energy. These values were determined by simulating the baseline home and summing all facility electricity and gas demand. For the GHP + PV combination system, the energy-efficiency upgrades achieved by replacing a residential building's space heating and cooling system with a geothermal heat pump system yielded the annual consumption for each location used in this analysis. The target value for photovoltaic electricity generation is the facility consumption value or the generation from a 12 kW array, whichever is lower.

Simulation of NZE analysis was executed through Building Energy Optimization Tool software (BEopt™). BEopt™ was designed by National Renewable Energy Laboratory in support of the U.S. Department of Energy [83]. The program provides a user-friendly graphical user interface to input home characteristics such as footprint, neighbor configuration, construction, systems, and appliances, among others. The same weather files are used as inputs to BEopt™ and EnergyPlus™. Once a simulation is activated, BEopt™ uses EnergyPlus™ as its background whole building simulation tool. In this study, the optimization feature within BEopt™ generated output for electricity generation by array capacity [kW] based upon azimuth and tilt angle. Array capacity can be varied from 0.5 kW to 12 kW, in 0.5 kW increments. The graphical user interface for a prototype home is shown in Figure 4.1. Each of the 12 cities used the same square footage, orientation, and neighboring home characteristics.

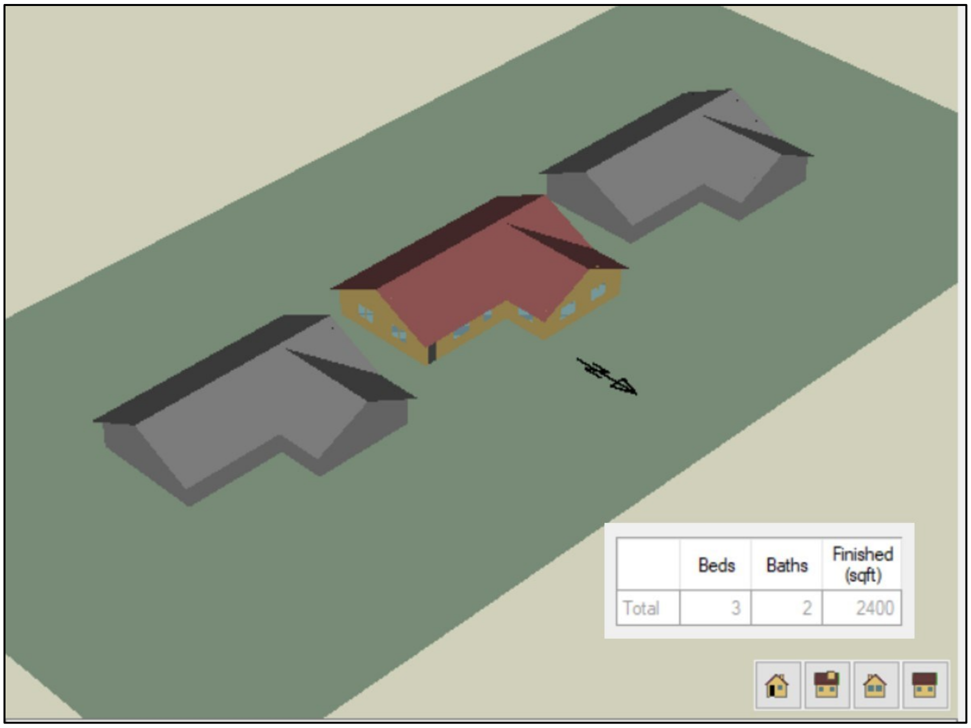


Figure 4.1 BEopt™ Graphical User Interface

Azimuth was held constant at 180°, or south facing, due to their locations in the Northern Hemisphere. The tilt angle was customized by latitude, longitude, and a weather factor using the procedure published by Christensen and Barker [84]. Optimization results reported the annual generation of each PV array. The array size chosen for each location was the one that generated electricity just exceeding the annual HVAC consumption. Each array was reported with an associated system cost per unit of energy of array size [$/W]. This dollar amount was used as the capital cost before incentives, $Cost_{cb,PV}$, for the PV complementary component. Once valued, a total system cost was determined for the combination system through Equation 4.1:

$$Cost_{cb,PV} + Cost_{cb,GHP} = Cost_{cb,total} \tag{4.1}$$

Once capital cost before incentives was summed from Equation 4.1, additional local incentives for solar photovoltaics were added to Table 3.7, resulting in Table 4.2.

Table 4.2 Financial Incentives by Technology and State [85]

Zone	City, State	Technology	Incentive	Details
1A	Miami, FL	Geothermal	Property Tax Abatement for Renewable Energy Property	100% of added value
		Solar	Property Tax Abatement for Renewable Energy Property	100% of added value
2B	Phoenix, AZ	Geothermal	Energy Equipment Property Tax Exemption	100% of increased value
		Solar	Residential Solar and Wind Energy Systems Tax Credit	25%, $1000 max
			Energy Equipment Property Tax Exemption	100% of increased value
3A	Memphis, TN	Geothermal	TVA Partner Utilities - eScore Program	Geothermal Heat Pump: $250/Unit
		Solar	Green Energy Property Tax Assessment	Property Tax Assessment, not to exceed 12.5% of installed cost
3B	Las Vegas, NV	Geothermal	N/A	N/A
		Solar	N/A	N/A
3C	Los Angeles, CA	Geothermal	N/A	N/A
		Solar	Property Tax Exclusion for Solar Energy Systems	100% of system value
			Solar Investment Tax Credit	$0.25/Watt of array size
4A	Baltimore, MD	Geothermal	Residential Clean Energy Rebate Program	New GHC: $3,000/project
		Solar	Residential Clean Energy Rebate Program	PV: $1,000/project (flat per installation/household incentive)
			Property Tax Exemption for Solar and Wind Energy Systems	100% real property tax exemption for solar and wind energy property
4C	Portland, OR	Geothermal	Renewable Energy Systems Exemption	100%
		Solar	Renewable Energy Systems Exemption	100%

Table 4.2 (continued)

5A	**Des Moines, IA**	**Geothermal**	**Property Tax Exemption for Renewable Energy Systems**	**Geothermal: 100% exemption for 10 years**
			Geothermal Heat Pump Tax Credit	20% of the Federal Tax Credit, equivalent to 6% of the system cost
		Solar	Solar Energy Systems Tax Credit (Personal)	15%
			Property Tax Exemption for Renewable Energy Systems	Solar and wind: 100% exemption for 5 years
5B	Reno, NV	Geothermal	N/A	N/A
		Solar	N/A	N/A
6B	Helena, MT	Geothermal	Renewable Energy Systems Exemption	100% for 10 years
			Residential Alternative Energy System Tax Credit	$500 per individual taxpayer; up to $1,000 per household
			Residential Geothermal Systems Credit	$1,500
		Solar	Renewable Energy Systems Exemption	100% for 10 years
			Residential Alternative Energy System Tax Credit	$500 per individual taxpayer; up to $1,000 per household
7A	Duluth, MN	Geothermal	N/A	N/A
		Solar	Wind and Solar-Electric (PV) Systems Exemption	Solar: 100% exemption from real property taxes
7B	Gunnison, CO	Geothermal	N/A	N/A
		Solar	Property Tax Exemption for Residential Renewable Energy Equipment	100% exemption for renewable energy system property

The net metering method requires an hour-by-hour analysis performed on the electricity generation from January 1 through December 31. Each hour's consumption was compared to its generation, and the energy purchased from the grid and sold back to the grid is calculated for each hour. The conditions in Table 4.3 explain how the values are calculated.

Table 4.3 Net Metering Conditions Hour-by-Hour

Hourly Data	E_{cons} [kW]	E_{gen} [kW]	E_{pur} [kW]		E_{sold} [kW]	
Strategy			if $E_{cons} > E_{gen}$	if $E_{cons} < E_{gen}$	if $E_{con}s < E_{gen}$	if $E_{cons} > E_{gen}$
			$E_{pur} = E_{cons} - E_{gen}$	$E_{pur} = 0$	$E_{sold} = E_{gen} - E_{cons}$	$E_{sold} = 0$

In a given hour, the energy consumed and the energy generated are recorded, E_{cons} and E_{gen}, respectively. The energy consumed for the baseline home is from the EnergyPlus™ simulation results with the traditional DX cooling / gas furnace HVAC system. The energy consumed for the GHP retrofit home are from the EnergyPlus™ simulation results in CHAPTER III. The energy generation data is from the BEopt™ simulation. If the energy consumed is greater than the energy generated, some or all of the energy will be purchased from the grid. If the energy consumed is less than the energy generated, the excess energy generated will be sold back to the grid. This comparison is performed for each hour of the day, each day of the year. Zhang et al. [86] defined a method of summation to determine the total surplus or deficiency in energy generation by a PV array. In just one day, the amount of energy generated minus the amount of energy consumed results in a value of $\Delta e = E_{gen} - E_{cons}$. In this study, the value of Δe is used to calculate the amount of energy either purchased or sold in a given hour. Of all the cities in the present study, the energy sold back to the grid is credited at a one-to-one rate [87] - [88]. Excess credits are rolled over to the next month, and credits remaining at the end of the year are compensated to the customer at varying rates. Rate structure for excess energy is shown in Table 4.4.

Table 4.4 Net Metering Compensation by Location

Zone	City, State	Excess Energy Compensation	Source
1A	Miami, FL	Retail rate = $0.1161	[87]
2B	Phoenix, AZ	Retail rate = $0.1284	[89]
3A	Memphis, TN	$0.09 if < 10kW; $0.075 if > 10 kW	[90]
3B	Las Vegas, NV	$0.08826	[91]
3C	Los Angeles, CA	Retail rate = $0.1890	[92]
4A	Baltimore, MD	Retail rate = $0.1333	[93]
4C	Portland, OR	Retail rate = $0.1092	[94]
5A	Des Moines, IA	Retail rate = $0.1267	[95]
5B	Reno, NV	$0.07175	[91]
6B	Helena, MT	Retail rate = 0.1118	[96]
7A	Duluth, MN	Retail rate = $0.1338	[97]
7B	Gunnison, CO	Wholesale rate (~2.5 times less than retail)	[88]

Using the energy consumption and generation data and applying compensation rates in Table 4.4, annual savings is calculated. For the baseline + PV system, cost differential is the annual operating cost before the PV complement to the annual operating cost with the PV complement. For the GHP + PV system, cost differential is the annual operating cost before the GHP + PV complement to the annual operating cost with the GHP + PV complement.

4.2.4 Payback Analysis

To consider the steadily increasing cost of utilities for residential building owners, the actual payback period (APP) method is used in this study. This simple method was introduced by Hanna [75] and relies heavily on selecting an accurate annual rate of increase of energy prices. Because this critical metric varies with time, a study by Sandoval [77] reports a 67% increase in energy prices from 2001 to 2014. This increase over the 14-year period averages to 5.15% rate increase annually, the value used in this study. For example, consider a home that experiences an annual utility savings, AS_n, of \$1,000 in the first year (n =1) after an energy-efficiency upgrade project. Then, AS_1 = 1,000. At an energy price increase of 5.15%, the savings at the end of the second year would be AS_2 = 1.0515*AS_1 = 1.0515*\$1,000 = \$1,051.50. Equation 4.2 generalizes the example across n years:

$$AS_n = 1.0515(AS_{n-1}) \tag{4.2}$$

Each year, the annual savings is subtracted from the dollar amount remaining on the initial capital investment. Twenty-five years is the expected useful system lifetime, so the net lifetime savings can be calculated from Equation 4.3:

$$Lifetime\ Net_{APP} = -Cost_{ca} + \sum_{n=1}^{n=25} AS_n \tag{4.3}$$

where $Cost_{ca}$ is the total capital investment after all incentives are applied. For the baseline + PV system, $Cost_{ca}$ is the cost of the PV system after incentives. For the GHP + PV system, $Cost_{ca}$ is the cost of the GHP + PV system after incentives.

4.3 NZE Results

Energy generation results for each of the 12 cities was analyzed hour-by-hour to quantify the net metering results. To explain the data breakdown, Figure 4.2 is an example of a one-week duration in Los Angeles, CA from July 1 at 12:00 AM to July 7 at 11:59 PM. As can be seen, although energy consumed, E_{cons}, peaks during the day and goes down at night, there is a consistent demand around the clock. In contrast, the energy generated, E_{gen}, spikes during the day and drops to zero at night when the sun is down.

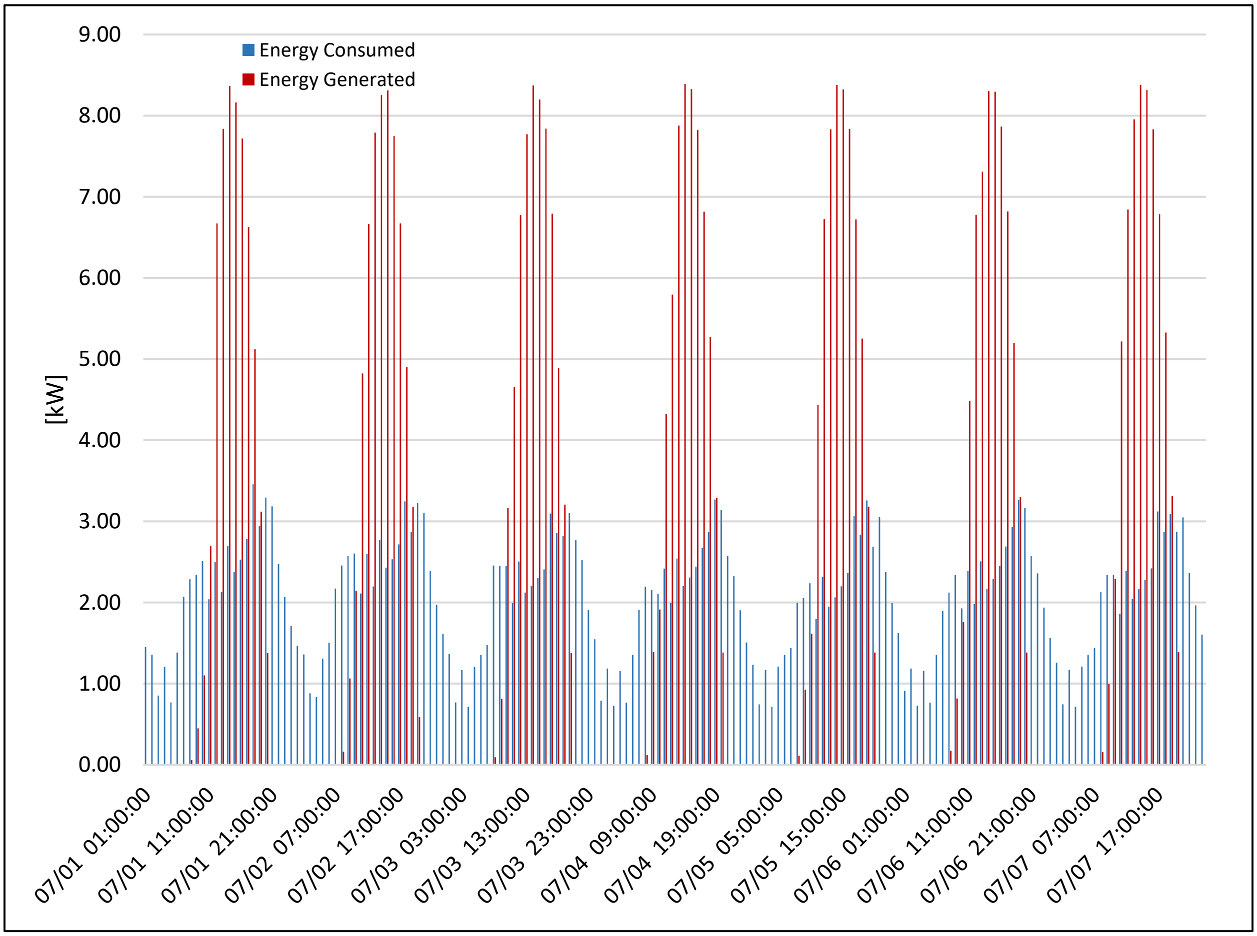


Figure 4.2 Los Angeles, CA Net Metering Data for One Week

Quantifying the electricity purchased and electricity sold to the grid requires this hourly breakdown. Adding to Table 4.3, Table 4.5 displays the results for two separate hours for Los Angeles, CA. On July 8 at 1:00 PM, the generation was higher than the demand, so zero electricity was purchased. The remainder was sold back to the grid. On October 25 at 7:00 PM, consumption was higher than generation, so a portion of the demand was purchased. Zero electricity was sold back to the grid.

Table 4.5 Net Metering Results Example for Los Angeles, CA

	[kW]	[kW]	[kW]		[kW]	
			$E_{pur} = E_{cons} - E_{gen}$	$E_{pur} = 0$	$E_{sold} = E_{gen} - E_{cons}$	$E_{sold} = 0$
10/25 19:00:00	2.90	0.76	2.14		0	

The comparative analysis shown in Table 4.5 was replicated for all 8,760 hours of the year in each of the 12 cities, for the baseline + PV system and the GHP + PV system. As stated in Section 2.1, Assumption #3, the PV array capacity was selected to either fully achieve NZE or it was chosen to be 12 kW, whichever was smaller. Los Angeles, CA was the only location that achieved true NZE with either HVAC + PV option, and the array capacity for that scenario was 12 kW. Therefore, the financial analysis of all 12 cities is based upon a PV array capacity of 12 kW. Detailed breakdowns of the energy results and annual savings for both system scenarios are given in Table 4.6.

Table 4.6 Energy Consumption, Generation, and Annual Savings by City

Zone	City, State	PV Array Size	Annual E_{cons} Baseline	Annual E_{gen}	Utility Cost	Annual Cost Baseline	Annual Cost	Annual Savings	Annual Cost	Annual Savings
							Baseline + PV		GHP + PV	
		[kW]	[kWh]	[kWh]	[$/kW]	[$]	[$]	[$]	[$]	[$]
1A	Miami, FL	12	21,228	16,442	0.1161	$ 2,465	$ 556	**$ 1,909**	$ 801	**$ 1,663**
2B	Phoenix, AZ	12	24,473	20,010	0.1196	$ 2,927	$ 534	**$ 2,393**	$ 538	**$ 2,389**
3A	Memphis, TN	12	26,114	16,116	0.1067	$ 2,786	$ 1,067	**$ 1,720**	$ 620	**$ 2,166**
3B	Las Vegas, NV	12	23,686	20,303	0.1186	$ 2,809	$ 401	**$ 2,408**	$ 166	**$ 2,644**
3C	Los Angeles, CA	12	17,855	18,592	0.1890	$ 3,375	$ (139)	**$ 3,514**	$ (191)	**$ 3,566**
4A	Baltimore, MD	12	29,723	15,752	0.1333	$ 3,962	$ 1,862	**$ 2,100**	$ 878	**$ 3,084**
4C	Portland, OR	12	26,312	13,534	0.1092	$ 2,873	$ 1,395	**$ 1,478**	$ 720	**$ 2,153**
5A	Des Moines, IA	12	36,652	16,767	0.1267	$ 4,644	$ 2,520	**$ 2,124**	$ 1,022	**$ 3,622**
5B	Reno, NV	12	28,729	19,260	0.1186	$ 3,407	$ 1,123	**$ 2,284**	$ 279	**$ 3,128**
6B	Helena, MT	12	34,628	16,651	0.1118	$ 3,871	$ 2,010	**$ 1,862**	$ 774	**$ 3,097**
7A	Duluth, MN	12	40,277	15,574	0.1338	$ 5,389	$ 3,305	**$ 2,084**	$ 1,486	**$ 3,903**
7B	Gunnison, CO	12	35,564	19,722	0.1214	$ 4,317	$ 1,923	**$ 2,394**	$ 576	**$ 3,742**

With the exceptions of Miami, FL and Phoenix, AZ, the cities achieved greater annual savings over the baseline home with the GHP + PV system than the baseline + PV system. The baseline + PV system achieved greater annual savings in the two cities of exception. This result is due to the zero or negative energy savings when these two baseline homes were retrofit with the GHP HVAC system [82]. With the PV array size selected from the performance data, all federal and local incentives were applied to capital costs, resulting in the capital cost after incentives, reported in Table 4.7.

Table 4.7 GHP + PV Combination System Capital Cost Before and After Incentives

Zone	City, State	$Cost_{cb,GHP}$	$Cost_{cb,PV}$	$Cost_{cb, total}$	Federal Credit	Local Discount	$Cost_{ca}$
1A	Miami, FL	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ 462	$ 30,084
2B	Phoenix, AZ	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ 1,348	$ 29,198
3A	Memphis, TN	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ 1,184	$ 29,363
3B	Las Vegas, NV	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ -	$ 30,547
3C	Los Angeles, CA	$ 8,000	$ 29,280	$ 37,280	$ 9,692	$ 3,468	$ 24,118
4A	Baltimore, MD	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ 4,483	$ 26,064
4C	Portland, OR	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ 549	$ 29,998
5A	Des Moines, IA	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ 5,788	$ 24,758
5B	Reno, NV	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ -	$ 30,547
6C	Helena, MT	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ 3,846	$ 26,700
7A	Duluth, MN	$ 12,000	$ 29,280	$ 41,280	$ 10,732	$ 497	$ 30,049
7B	Gunnison, CO	$ 8,000	$ 29,280	$ 37,280	$ 9,692	$ 93	$ 27,494

Figure 4.3 displays the payback period results for the baseline + PV system and the GHP + PV system that will move toward NZE across the 12 U.S. climate zones. A distinct delineation exists between climate zones 1-3 and climate zones 4-7. Each climate zone deserves its own commentary, as the results are quite revealing in terms of geographical location, sun exposure, soil type, and climate.

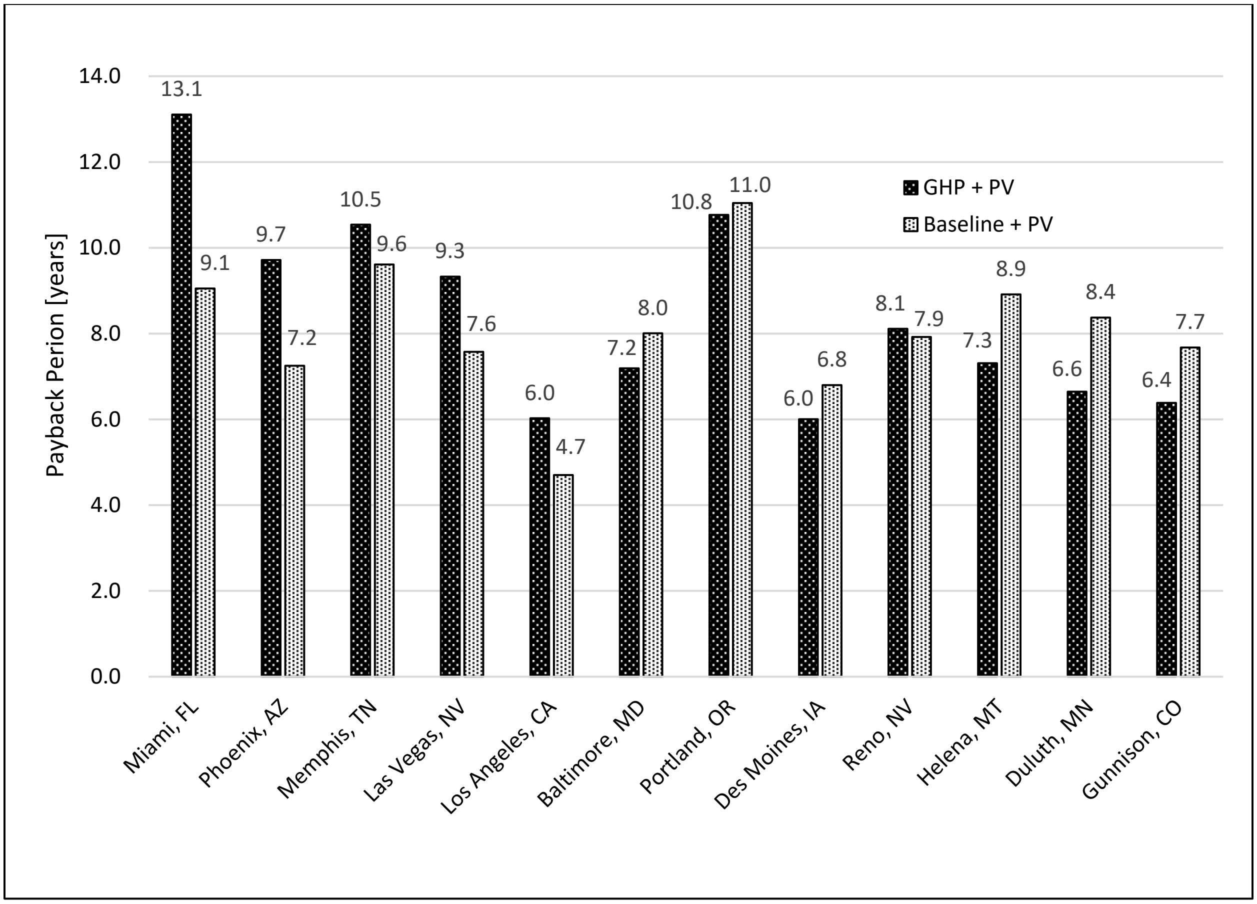


Figure 4.3 NZE System Payback Comparison

Results shown reflect the payback as determined using the actual payback period (APP) method.

If a system decision was based on the payback period alone, several would be challenging because the numbers for both systems are comparable. For example, Reno, NV has a mere $\left|\frac{(8.1\,years)-(7.9\,years)}{(8.1+7.9)years/2}\right| \times 100 = 2.5\%$ difference in payback period between the two systems. While the payback period is a valuable metric, the system lifetime savings provides the long-term financial outlook of the NZE systems. After all, a homeowner may accept a longer payback period in order to achieve a greater return on investment over the life of the system. Therefore, Figure 4.4 displays the lifetime system savings of both the baseline + PV system and the GHP + PV system.

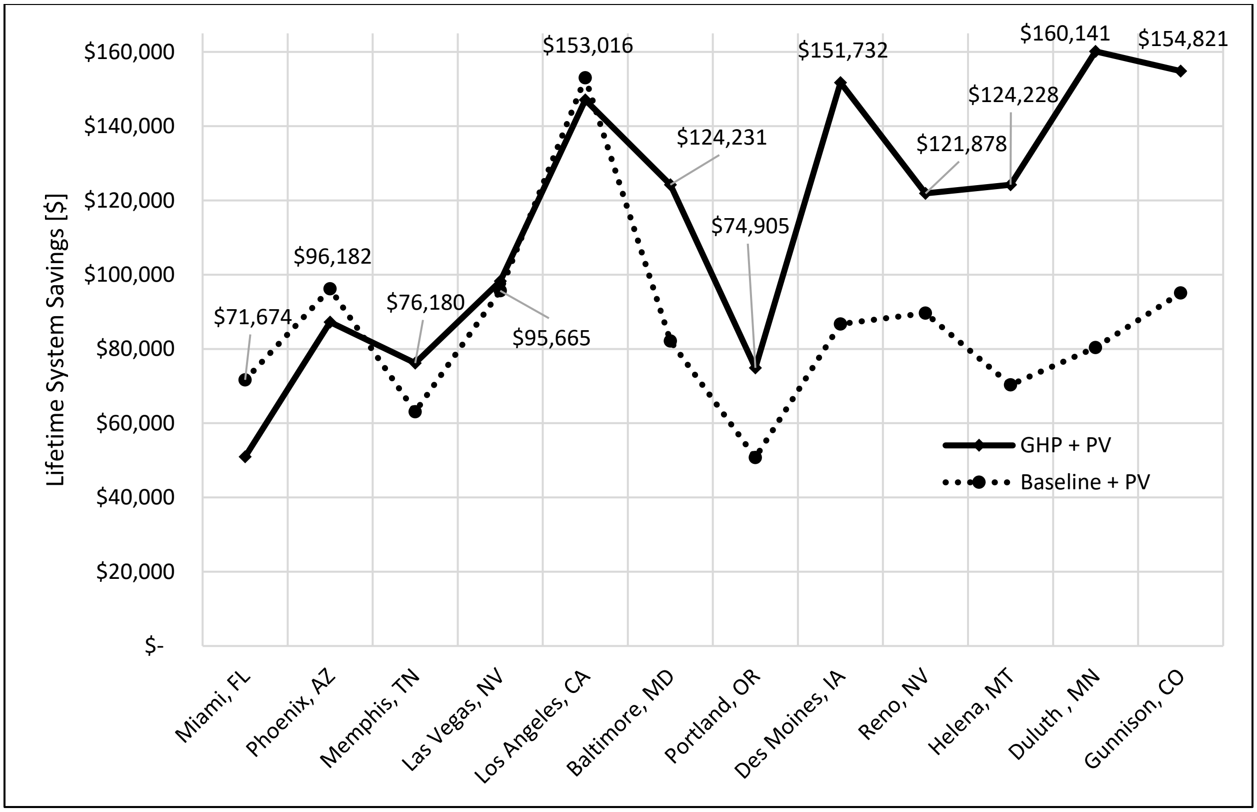


Figure 4.4 NZE Lifetime System Savings Comparison

Results shown reflect the lifetime system savings as determined using the actual payback period (APP) method.

Obtaining this second financial measure clarifies the more lucrative system savings over the lifetime of the system. The preferred system was unclear in Reno, NV by only assessing the payback periods, but the lifetime system savings data identifies the GHP + PV system as preferred. Table 4.8 summarizes the shorter payback period system and the higher lifetime system savings for each climate zone. From these two metrics, the preferred NZE system is determined and reported.

Table 4.8 Preferred NZE System Based on Payback and Lifetime Savings Comparison

Zone	City, State	Shorter Payback	Higher Lifetime System Savings	Preferred NZE System
1A	Miami, FL	PV	PV	**PV**
2B	Phoenix, AZ	PV	PV	**PV**
3A	Memphis, TN	PV	GHP + PV	**GHP + PV**
3B	Las Vegas, NV	PV	PV	**PV**
3C	Los Angeles, CA	PV	PV	**PV**
4A	Baltimore, MD	GHP + PV	GHP + PV	**GHP + PV**
4C	Portland, OR	GHP + PV	GHP + PV	**GHP + PV**
5A	Des Moines, IA	GHP + PV	GHP + PV	**GHP + PV**
5B	Reno, NV	PV	GHP + PV	**GHP + PV**
6B	Helena, MT	GHP + PV	GHP + PV	**GHP + PV**
7A	Duluth, MN	GHP + PV	GHP + PV	**GHP + PV**
7B	Gunnison, CO	GHP + PV	GHP + PV	**GHP + PV**

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For two of the locations, Memphis, TN and Reno, NV, the shorter payback and higher lifetime savings resulted from two different systems. Here, the preferred system is not as apparent as if both factors pointed to the same system. While the payback was shorter for the baseline + PV system alone, the GHP + PV system yielded higher lifetime system savings and was ultimately selected as the preferred system. Both cities experience a heating demand in the winter months, as well, also lending support to the economic benefits of the GHP component. Another important note, both Memphis, TN and Reno, NV had weak local incentive structures for PV and GHP initiatives, as shown in Table 4.2. Greater incentives for GHP technology in these climate zones would drive down the payback period for the GHP + PV system and encourage the shift away from fossil fuel-based space heating and cooling.

4.3.1 Discussion

To fully decipher the preferred NZE system results shown in Table 4.8, several classification schemes were generated to assign a score to each city in reference to sun intensity, soil thermal conductivity, and local financial incentive structure. These three variables have great impact on the appeal of the baseline + PV system versus a GHP + PV combination system.

A sun intensity rating was assigned to each city as strong, intermediate or mild. Based on the National Renewable Energy Laboratory (NREL) Global Horizontal Solar Irradiance Map, shown in Figure 4.5, each city was assigned a sun intensity rating [98]. The scale developed for this study is given in Table 4.9.

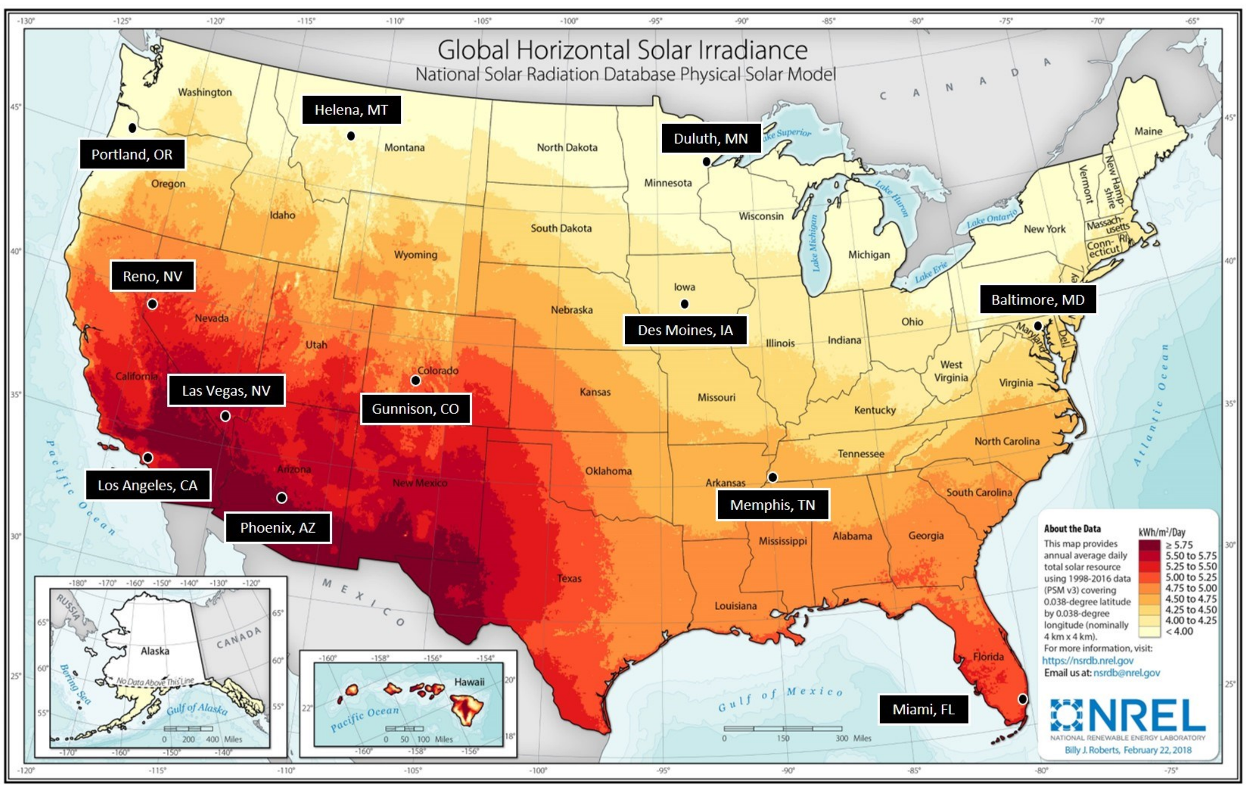

Figure 4.5 NREL Solar Irradiation Map [98]

National Renewable Energy Laboratory, “U.S State Solar Resource Maps,” *Geospatial Data Science*, 2020. [Online]. Available: https://www.nrel.gov/gis/solar.html. [Accessed: 06-Jan-2020].

The sun intensity rating, R_s, is assigned to each city representing its location on the scale given in Figure 4.5. If a city is in the top third of solar irradiation, middle third, or lowest third it is assigned a R_s of strong, moderate, or mild, respectively. Rating scale is given in Table 4.9.

Table 4.9 Sun Intensity Rating Scale

Sun Intensity Rating, R_s	**i_s [kWh/m²/day]**
Strong	> 5.25
Moderate	$5.25 > i_s > 4.50$
Mild	< 4.50

A soil conductivity classification, C_k, was assigned to each city as high, moderate or low. The lowest and highest soil thermal conductivities of the 12 sites are $k = 1.009\,\frac{W}{m \cdot K}$ and $k = 2.307\,\frac{W}{m \cdot K}$, respectively [82]. A full listing of soil thermal conductivities in all locations can be seen in the Appendix B, Table B.2. To arrive at the scale, the range of soil conductivities of the 12 locations was divided into three equal ranges Cities were assigned C_k as low, middle, and high based on which range segment its soil conductivity lies. The scale developed in this study is shown in Table 4.10.

Table 4.10 Soil Conductivity Classification Scale

Soil Conductivity Classification, C_k	**k [W/m-K]**
Low	1.009 to 1.442
Middle	1.443 to 1.874
High	1.875 to 2.307

A local incentive structure strength was assigned to each city as robust, mediocre or weak. To arrive at the multiplier, i_M, analysis was performed on the local incentives and the resulting percentage discount it achieves on the initial capital investment of the GHP + PV combination system. The highest percentage discount was in Des Moines, IA and its local incentives achieve a 14.024% discount. This value was designated as i_{max}, against which all other cities are compared. The remaining cities' percent discounts were divided by i_{max}, resulting in a percentage of i_{max} which becomes the coefficient of the multiplier, i_M. For example, the local incentives in Baltimore, MD achieved a percentage discount of 10.860%. Dividing this value by i_{max} yields 0.14024/0.10860 = 0.77. Thus, Baltimore's i_M is $0.77i_{max}$, where 0.77 is the coefficient. If the coefficient is in the top 33%, middle 33% or lowest 33% it is assigned S_i of robust, mediocre, or weak, respectively. The scale developed in this study is shown in Table 4.11. A full listing of local incentive percent discount for all locations can be seen in the Appendix B, Table B.2.

Table 4.11 Incentive Structure Strength Scale

Incentive Structure Strength Factor, S_i	Multiplier, i_M
Robust	$i_M \geq 0.66i_{max}$
Mediocre	$0.66i_{max} > i_M > 0.33i_{max}$
Weak	$i_M \leq 0.33i_{max}$

As seen in Table 4.12, the R_i, C_k and S_i ratings are compiled by city. The final column is the preferred energy-efficiency/net zero energy (EE/NZE) system as reported in Table 4.8. Recall, Recall, the preferred system is the one that achieved the shortest payback period/highest lifetime system savings by comparing the baseline + PV system versus GHP + PV combination system outlined in this research.

Table 4.12 Key Contributor Rankings

Zone	City, State	Sun Intensity Rating, R_i	Soil Conductivity Class, C_k	Incentive Structure Strength, S_i	Preferred EE/NZE System
1A	Miami, FL	Strong	Middle	Weak	PV
2B	Phoenix, AZ	Strong	Low	Weak	PV
3A	Memphis, TN	Intermediate	High	Weak	GHP + PV
3B	Las Vegas, NV	Strong	Middle	Weak	PV
3C	Los Angeles, CA	Strong	Low	Robust	PV
4A	Baltimore, MD	Mild	High	Robust	GHP + PV
4C	Portland, OR	Mild	High	Weak	GHP + PV
5A	Des Moines, IA	Mild	Middle	Robust	GHP + PV
5B	Reno, NV	Strong	High	Weak	GHP + PV
6B	Helena, MT	Mild	Middle	Robust	GHP + PV
7A	Duluth, MN	Mild	High	Weak	GHP + PV
7B	Gunnison, CO	Intermediate	High	Weak	GHP + PV

Numerous observations and associated implications are extractable from Table 4.12. Correlations between sun, soil, incentives, and the resulting preferred system are realized and allow for future interpolation of other locations. The observations and implications have been summarized in Table 4.13.

Table 4.13 Final Observations and Implications

Observation 1	Five cities ranked strong for R_i, sun intensity rating. Of these five, four yielded the PV system as the preferred EE/NZE choice.
Implication 1	A city that will benefit more from the PV system alone will likely have a strong sun intensity rating.
Observation 2	The one city with a strong sun intensity rating that yielded the GHP + PV system as preferred has a high soil conductivity class.
Implication 2	A strong sun intensity rating does not guarantee the PV system alone as preferred. If the GHP + PV system results as the preferred option, the city likely has a high soil conductivity class.

Table 4.13 (continued)

Observation 3	The four cities that resulted in PV system alone as preferred all have a middle or low C_k, soil conductivity class.
Implication 3	A city with a strong sun intensity rating and a low or middle soil conductivity class will yield the PV system alone as preferred.
Observation 4	All five cities with strong R_i have a weak incentive structure strength, S_i.
Implication 4	With a more sophisticated incentive structure, the PV system would experience shorter payback periods and higher public interest.
Observation 5	The one city with a strong sun intensity rating that yielded the GHP + PV system as preferred (5B) has a heating demand in heating season.
Implication 5	Even with a strong sun intensity rating, a city will yield GHP + PV system preferred if it experiences at least a moderate heating demand.
Observation 6	The remaining 7 cities yielded the GHP + PV combination system as preferred. All 7 of these cities have a moderate to high heating demand in the heating season.
Implication 6	Regardless of sun intensity rating, if a city has a moderate to high heating demand, the GHP + PV system will likely be preferred.
Observation 7	The two cities with low soil conductivity class did not yield GHP + PV system as preferred.
Implication 7	Soil conductivity class is directly proportional to the ultimate preferability of the GHP + PV combination system.
Observation 8	The one city with a strong sun intensity rating and high soil conductivity class yielded the GHP + PV system as preferred, but also has a weak incentive structure strength.
Implication 8	With a more sophisticated incentive structure, the strong sun intensity/high soil conductivity combination will have shorter payback periods and greater public interest may result.

Of note, simultaneous with the results of this research coming to light, the Federal Residential Renewable Energy Tax Credit dropped from 30% to 26% with the arrival of 2020. This new percentage was used for the payback period calculation for all 12 cities in this NZE investigation. While this incentive decrease may not deter a potential customer, the trend toward reduce financial incentives certainly works against the prevailing barrier of high capital investment to widespread deployment. The Federal Residential Renewable Energy Tax Credit is due to decrease from 26% to 22% in the year 2021.

4.4 Consumer Decision Drivers

In CHAPTER III, our research led to the nagging question of "what will people accept?" in reference to financial savings and payback period for renewable energy options. A survey classification led to quantifying the answer based upon percentages of the population that are willing accept the payback calculated for climate zones across the U.S. While this is a logical attempt at arriving at an answer through methodical means, a piece was missing that was difficult to identify. The actions and decisions of homeowners still seemed very challenging to predict. So, once all financial information is presented, what ultimately triggers one homeowner to act on renewable energy and the other to resist? Certainly, a low payback period, high energy savings portfolio could be presented to two different homeowners, and their different reactions would not be surprising. As stated, despite all the facts, the final decision is a personal choice. How do we address the softer, less measurable factors? This question led to an investigation into the sociology behind renewable energy perceptions.

Interesting links between personal affiliations and the environment are a popular topic of study. Because of the eliminated reliance on fossil fuels, residential geothermal heating and cooling is considered environmentally friendly. Solar photovoltaics fall into this category for the same reason. Both technologies are inexhaustible energy sources, so they are referred to by a broader categorization of renewable energy in the context of pro-environment options. In reference to environmental issues, Arpan et al. [99] tested the hypothesis that political orientation and an individual's value framework drive their magnitude of environmental concern. Specifically, whether one identifies as liberal or conservative will heighten or detract from an interest in environmentally beneficial initiatives. To test the hypothesis, advertisements for environmental products were presented to survey participants from two different moral domains, harm/care and purity. As defined by moral foundation theory, the domain of harm/care refers to a moral stance that prioritizes safety and well-being of others [100]. The domain of purity prioritizes cleanliness of surroundings and opposition to degradation. Typically, liberals are moved by messages of the harm/care domain and conservatives connect to messages of the purity domain. Regardless of the test subject's affiliation as either liberal or conservative, they were provided a product advertisement from one of the two domains. Results concluded that message framing, or tailoring the moral domain to the audience, did not significantly change the appeal of renewable energy use in liberal or conservative thinkers.

The verdict is not conclusive on the findings by Arpan et al. [99]. Feinburg and Willer [101] also studied the impacts of moral values of purity and harm/care on one's attitude toward the environment. Their research defines "segmentation" as the phenomenon that different groups of people will be motivated and affected by different strategies of message framing. If individuals view environmental harm as a personal responsibility, the more likely they are to view stewardship to the environment as a moral obligation; and moral campaigns are historically more effective than nonmoral campaigns. Their study proved that most pro-environment appeals are of the harm/care domain rather than the purity domain, and thus attract more liberal than conservative individuals. Reframing for varied audiences will unite opposing sides of the environmental issues. For a consumer, viewing an advertisement that originates from the same moral domain as the viewer will be attractive, because the conveyor of the message is perceived as a trusted and fellow ally.

In a similar investigation, Perlaviciuite and Steg [102] study “biospheric” versus “egoistic” valued individuals. Biospheric individuals are those that value nature, egoistic are those that value wealth. Their findings prove that biospheric and egoistic individuals are drawn to different components of renewable energy. Biospheric thinkers are attracted to the movement from non-renewable to renewable energy for longevity of the planet. Egoistic thinkers are attracted to the financial savings potential of consumer-generated electricity and reduced energy use technologies. However, they stated that if individual negative financial consequences are too great, the biospheric nature of an individual is likely not strong enough to convince one to pursue the alternative. The individualized impact trumps the altruism. In summary, Perlaviciute et al. [102] claimed that environmental campaigns across the population are more persuasive than financial campaigns, and energy policies should always aim to speak to group-specific values.

The studies cited on the sociology of renewable energy bring a new light to the overall investigation of NZE systems. They bring awareness to the fact that, despite the most attractive financial profile to a homeowner, there are many more intangible factors that will sway the consumer to adopt renewable energy in the home or not. These factors include individual political affinity and moral values, consumer financial health, age, gender, level of education and even religious identity [99] [101] [102]. As shown in Figure 4.3, all cities studied boast a payback period of less than 10 years for the preferred NZE system. However, the soft factors make widespread adoption difficult to predict and highly variable. Message framing and energy policy advocation that attempts to connect with highly varied moral domains may capture more customers than a neutral approach. Engineers research the technology and sociologists study the behavior, both crucial components of the decision to pursue residential renewable energy.

4.5 Chapter Summary

This chapter focused on the residential sector in the United States. A net-zero energy system comprised of a PV electricity generation array added to a traditional, electric cooling / natural gas heating system was compared to a PV net-zero energy system paired with a geothermal HVAC system. The energy and financial implications of the two options technology are reported. Communities across the nation in many climate zones are investigated to arrive at a comprehensive profile of performance and financial incentives.

CHAPTER V

CONCLUSIONS

In this dissertation, focus was on the residential sector in the United States. A renewable energy heating and cooling system comprised of a geothermal heat pump was thoroughly analyzed and compared to a more traditional, electric cooling / natural gas heating system. The energy and financial implications of this change in technology are reported. Communities across the nation in many climate zones are investigated to arrive at a comprehensive profile of performance and financial incentives. CHAPTER I provided a review of the existing database of information on national and global technological and financial strides for renewable energy, geothermal specifically. Design optimization efforts included borefield design, pipe material, grout material, thermal enhancements to pipe and grout, and choosing the proper heat pump size. Despite technological and economic advancement, geothermal technology spread worldwide is slow. Communities, leaders, and individuals are hesitant for several reasons, the two top barriers being initial capital investment and lack of knowledge. Creative measures have been attempted across the globe to mitigate the high cost. Some attempts are stable, some are cyclic, and some have failed. Published literature proves that efforts are well-documented for attempts to optimize performance and incentivize all sectors to implement geothermal technology.

CHAPTER II focused on the mathematical process of designing a location-specific borefield through the consideration of weather profile, soil thermal and physical characteristics. Without relying on region averages, the calculations are specific to a single-family home residence's specific physical address. With this precision, this home's profile may vary from a neighbor across the street. Exciting energy savings and financial results are discovered for a home in Memphis, Tennessee. The Memphis, TN prototype home achieved an annual energy savings of 26%. This number is only one factor for consideration, however. Perhaps even more important to the homeowner is the payback period. Through application of federal and location-specific incentives, a reliable payback period is reported. For the subject home, a payback period of over 15 years. Human interest polls show that this is too long for most consumers to accept, and increased incentive structures would be necessary to decrease the payback period to an acceptable duration. A key takeaway from CHAPTER II is that geothermal space heating and cooling systems show promise for high energy savings in heating-dominant climates. In this chapter, a template method of analysis was created that allow for similar analysis of other locations for residential geothermal viability.

CHAPTER III widens the study of residential geothermal viability to the contiguous United States. The 12 climate zones investigated characterize a diverse collection of temperature and humidity profiles, ranging from hot / humid in Miami, Florida to cold / dry in Gunnison, Colorado. 10 out of the 12 climate zones resulted in annual energy savings with the geothermal system over the baseline electric cooling / natural gas heating system. The highest energy savings was in Helena, Montana at an astounding 59%. However, even in cities that had net positive energy savings, the annual financial savings and payback period is the metric more crucial to the consumer. Using the template developed in CHAPTER II, all local incentives were compiled to arrive at the promising payback results for several climate zones. Helena, Montana also achieved the shortest payback period at only 3.2 years. The results were not so attractive for other cities, with Los Angeles, California resulting in a payback of over 35 years. The chapter effectively provides a diverse climate prediction of residential geothermal performance and financial implications.

CHAPTER IV dove deeper into the possibility of the net-zero energy residential building, a rapidly rising goal in communities globally. While a catchy phrase, the technical and financial reality of arriving at this label is a challenge worth investigating. Building upon the energy results from the geothermal system, a solar photovoltaic array is added as a complementary system (GHP + PV) to each of the 12 residences. The GHP + PV combination system NZE potential was compared to a PV system added to the baseline home, prior to any GHP energy-efficiency modifications. Updated payback data and lifetime savings for both options are calculated and compared. Ultimately, the preferred system is identified for each climate zone. Three new variables are defined in this analysis: soil conductivity classification (C_k), sun intensity rating (R_i), and incentive structure strength factor (S_i). Combinations of these three new descriptive variables help make observations and implications of the 12 cities of interest. An exciting takeaway from this investigation is the ability to apply these three variables to any city in the country, and predict what the preferred system will likely be through comparison to the original sample. The larger the database of cities that undergo the complete simulation and financial analysis, the more accurate the three predictors will become. A key contribution of this chapter is the examination of the intangible factors of human nature that drive ultimate consumer decisions. Fascinating revelations about human moral domains and personal profiling reveal a potential avenue for sparking interest in renewable energy projects in all consumers.

The outcome of this dissertation is an exciting catalyst for continued work. Significant conclusions of the research performed lead to the following action items for future work:

- Conduct sensitivity analysis of payback period to design parameters of the ground source heat pump system. Parameters to be varied include thermal conductivity of grout and pipe, pipe thermal enhancement characteristics, pipe diameter, porosity of soil, and borefield characteristics.
- Further refine location-specific initial capital investment predictions through interviews with local contractors, geothermal heat pump distributors, construction firms and construction cost data.
- Expand the scope of investigation to additional single-family residential buildings across the country.
- Conduct human interest surveys in the United States equipped with data on consumption savings, payback period, and lifetime savings.
- Attempt to quantify consumer interest considering the intangible factors of human perception, message framing, and environmentally appropriate moral values.

REFERENCES

[1] X. Liu, A. Anderson, P. Hughes, and J. Spitler, "An Updated Assessment of the Technical Potential of Geothermal Heat Pump Applications in the United States," in *IGSHPA Technical/Research Conference and Expo*, 2017.

[2] C. C. Michelsen and R. Madlener, "Homeowners ' preferences for adopting innovative residential heating systems : A discrete choice analysis for Germany," *Energy Econ.*, vol. 34, no. 5, pp. 1271–1283, 2012.

[3] S. Karytsas and I. Choropanitis, "Barriers against and actions towards renewable energy technologies di ff usion : A Principal Component Analysis for residential ground source heat pump (GSHP) systems," *Renew. Sustain. Energy Rev.*, vol. 78, no. April, pp. 252–271, 2017.

[4] S. Kavanaugh and C. Gray, "A Simple Approach To Affordable GSHPs," *Ashrae J.*, no. April, pp. 14–24, 2016.

[5] T. H. Lim, R. D. De Kleine, and G. A. Keoleian, "Energy use and carbon reduction potentials from residential ground source heat pumps considering spatial and economic barriers," *Energy Build.*, vol. 128, pp. 287–304, 2016.

[6] B. M. Sonnier, "Property Tax Exemptions for Residential Renewable Energy Equipment and Systems," *Taxes The Tax Magazine*, pp. 21–24, 2017.

[7] H. H. Thorsteinsson and J. W. T. Ã, "Barriers and enablers to geothermal district heating system development in the United States," *Energy Policy*, vol. 38, no. 2, pp. 803–813, 2010.

[8] T. J. Reber, K. F. Beckers, and J. W. Tester, "The transformative potential of geothermal heating in the U . S . energy market : A regional study of New York and Pennsylvania," *Energy Policy*, vol. 70, pp. 30–44, 2014.

[9] M. Pacesila, "GEOTHERMAL ENERGY : CURRENT STATUS AND FUTURE DEVELOPMENT IN EUROPEAN," *Manag. Res. Pract.*, vol. 8, no. 3, pp. 5–17, 2016.

[10] P. Eslami-Nejad, Z. Aidoun, A. Hakkaki-Ford, and M. Ouzzane, "Technical Assessment of Ground-Source, Air-Source, and Hybrid Heat Pumps for Single-Family Buildings in Cold Climates," *ASHRAE Trans.*, vol. 122, no. 2, pp. 270–280, 2016.

[11] Z. Sagia, A. Stegou, and C. Rakopoulos, “Parametric Analysis of Geothermal Residential Heating and Cooling Application,” *Int. J. Energy Environ.*, vol. 3, no. 5, pp. 701–714, 2012.

[12] J. D. Spitler, “Latest Developments and Trends in Ground-Source Heat Pump Technology,” in *European Geothermal Congress*, 2016, pp. 1–7.

[13] N. Dhepe and R. Krishna, “A Review of the Advancements in Geothermal Heating and Cooling System,” *J. Altern. Energy Sources Technol.*, vol. 8, no. 1, pp. 1–5, 2017.

[14] T. H. Lim, “Geothermal Heat Pump System for U.S. Residential Houses: Barriers of Implementation and its Environmental and Economic Benefits,” University of Michigan, 2014.

[15] S. Karytsas, O. Polyzou, and C. Karytsas, “Factors affecting willingness to adopt and willingness to pay for a residential hybrid system that provides heating / cooling and domestic hot water,” *Renew. Energy*, vol. 142, pp. 591–603, 2019.

[16] I. Terzic, V. Sustersic, and K. Donovic, “Comparative Analysis of Geothermal Heat Pumps,” *ACTA Tech. CORVINIENSIS - Bull. Eng.*, vol. 11, no. 1, 2018.

[17] P. Dumas, “A European perspective of the development of deep geothermal in urban areas,” *Geomech. Tunn.*, vol. 9, no. October 2016, pp. 447–450, 2016.

[18] European Climate Foundation, “Roadmap 2050 Volume 1: Technical and Economic Analysis,” The Netherlands, 2010.

[19] U.S. Environmental Protection Agency, “A Complete Heating and Cooling System,” 2017.

[20] U.S. Environmental Protection Agency, “A Complete Water Management System,” 2017.

[21] U.S. Environmental Protection Agency, “Complete Thermal Enclosure,” 2017.

[22] U.S. Environmental Protection Agency, “Efficient Lighting and Appliances,” 2017.

[23] U.S. Department of Energy, “DOE Zero Energy Ready Home National Program Requirements,” 2017.

[24] Zero Energy Project, “Energy Efficiency Incentives and Tax Credits.” [Online]. Available: https://zeroenergyproject.org/build/loan-programs-incentives-tax-credits-energy-efficiency/.

[25] U.S. Department of Energy, “Renewable Energy Ready Home Solar Site Assessment Tool.” [Online]. Available: https://www.energystar.gov/index.cfm?c=rerh.assessment. [Accessed: 19-Jun-2018].

[26] New York City Department of Design and Construction, “Geothermal Tool,” *Geothermal Pre-Feasibility Tool*, 2018. [Online]. Available: https://www1.nyc.gov/assets/ddc/geothermal/index.html. [Accessed: 09-Jul-2019].

[27] U.S. Environmental Protection Agency, “2017 Renewable Energy Tax Credits.” [Online]. Available: https://www.energystar.gov/about/federal_tax_credits/2017_renewable_energy_tax_credits.

[28] DSIRE NC Clean Energy Technology Center, “FHA PowerSaver Loan Program.” [Online]. Available: http://programs.dsireusa.org/system/program/detail/5631.

[29] U.S. Department of Energy, “Heating & Cooling.” [Online]. Available: https://www.energy.gov/articles/history-air-conditioning. [Accessed: 17-Feb-2019].

[30] Memphis Light Gas and Water Division, “2019 Utility Bill Comparisons for Selected Cities,” no. January 2019. Memphis, TN, pp. 2–5, 2019.

[31] R. G. Newell and J. V Siikamaki, “Individual time preferences and energy efficiency,” Cambridge, MA, 20969, 2015.

[32] W. Goetzler, M. Guernsey, and R. Kar, “Research and Development Roadmap: Geothermal (Ground-Source) Heat Pumps,” 2012.

[33] U.S. Department of Energy, “EnergyPlus.” Building Technologies Office (BTO), 2019.

[34] J. Zhang, A. Knizley, and H. Cho, “Investigation of existing financial incentive policies for solar photovoltaic systems in U . S . regions,” *AIMS Energy*, vol. 5, no. October, pp. 974–996, 2017.

[35] M. Philippe, M. Bernier, and D. Marchio, “Vertical Geothermal Borefields Sizing Calculation Spreadsheet,” *Ashrae J.*, no. July 2010, pp. 20–28, 2010.

[36] S. Cho and S. Mirianhosseinabadi, “Simulation Modeling of Ground Source Heat Pump Systems for the Performance Analysis of Residential Buildings,” *Proc. BS2013 13th Conf. Int. Build. Perform. Simul. Assoc.*, pp. 1960–1967, 2013.

[37] U.S. Department of Energy, “Residential Prototype Building Models,” 2012. [Online]. Available: https://www.energycodes.gov/development/residential/iecc_models. [Accessed: 25-Feb-2020].

[38] U.S. Department of Energy, “Building Performance Database,” *Lawrence Berkeley National Laboratory*. [Online]. Available: https://bpd.lbl.gov/#explore. [Accessed: 04-May-2019].

[39] U.S. Department of Energy, “EnergyPlus Version 8.9.0 Documentation Input Output Reference.” p. 82, 2018.

[40] D. Kang and H. Cho, “Modeling of central ground-source heat pump system in EnergyPlus,” in *Asim 2016, The 3rd Asia conference of International Building Performance Simulation Association*, 2016, no. December.

[41] Bosch Thermotechnology Corp., “Bosch Greensource SM Series Residential Geothermal Heat Pump.” Bosch-Climate, Londonderry, NH, pp. 1–37.

[42] United States Department of Agriculture (USDA), “Web Soil Survey.” [Online]. Available: https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx. [Accessed: 25-Feb-2020].

[43] International Ground Source Heat Pump Association, *Soil and Rock Classification for the Design of Ground-Coupled Heat Pump Systems*, 1st ed. Stillwater, OK, 1989.

[44] Virginia Tech, “Soil Data for the Design of Geothermal Heat Pumps.” [Online]. Available: http://www.geo4va.vt.edu/A1/A1.htm.

[45] B. Tong, “An Empirical Model for Estimating Soil Thermal Conductivity from Soil Water Content and Porosity,” *J. Hydrometeorol.*, vol. 17, p. 602, 2016.

[46] T. J. Longwell, W. L. Parks, M. E. Springer, and University of Tennessee Agricultural Experiment Station, “Moisture Characteristics of Tennessee Soils,” *Bulletins*, no. 367, p. 26, 1963.

[47] StructX, “Density Ranges for Different Soil Types.” [Online]. Available: http://structx.com/Soil_Properties_002.html. [Accessed: 25-Feb-2020].

[48] United States Energy Information Administration, “Electricity Data Browser,” *October 2008*. [Online]. Available: https://www.eia.gov/electricity/data/browser/. [Accessed: 17-Feb-2019].

[49] NC Clean Energy Technology Center, “Programs (TN),” *DSIRE*, 1995. [Online]. Available: http://programs.dsireusa.org/system/program?fromSir=0&state=TN. [Accessed: 17-Feb-2018].

[50] S. Yard, “Developments of the Payback Method,” *Int. J. Prod. Econ.*, vol. 67, no. 2, pp. 155–167, 2000.

[51] P. D. Lavappa and J. D. Kneifel, “Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – 2018 Annual Supplement to NIST Handbook 135,” 2018.

[52] Office of Management and Budget, “Circular A-94 Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs,” 2018.

[53] Office of Management and Budget, *Circular A-4, Regulatory Analysis*. Office of Management and Budget, 2004, pp. 1–48.

[54] ASHRAE, *2019 ASHRAE Handbook - Applications*, 2019th ed. Atlanta, GA, 2019.

[55] J. Zhang, H. Cho, R. Luck, and P. Mago, "Integrated photovoltaic and battery energy storage (PV-BES) systems: An analysis of existing financial incentive policies in the US," *Appl. Energy*, no. 212, pp. 895–908, 2018.

[56] R. Neves, H. Cho, and J. Zhang, "Techno-Economic analysis of geothermal system in residential building in Memphis, Tennessee," *J. Build. Eng.*, vol. 27, no. January 2020, 2020.

[57] J. Zhang, H. Cho, and A. Knizley, "Evaluation of financial incentives for combined heat and power (CHP) systems in US regions," *Renew. Sustain. Energy Rev.*, no. 59, pp. 738–762, 2016.

[58] U.S. Department of Energy, "Guide to Determining Climate Regions by County," vol. 7.3, no. August, 2015.

[59] McQuay, "Geothermal Heat Pump Design Manual," 2002.

[60] T. Abichou, C. Wang, T. Kormi, and J. Chanton, "A novel approach to estimate methane oxidation in interim landfill covers across the USA.," *Int. J. Environ. Waste Manag.*, vol. 15, no. June, p. 309, 2015.

[61] I. AccuWeather, "AccuWeather," 2019. [Online]. Available: https://www.accuweather.com/. [Accessed: 25-Feb-2020].

[62] Energy Star, "Degree Days Calculator," *Portfolio Manager*. [Online]. Available: https://portfoliomanager.energystar.gov/pm/degreeDaysCalculator. [Accessed: 25-Feb-2020].

[63] National Oceanic and Atmospheric Administration Center, "Global Climate Station Summaries," *National Climactic Data Center*. [Online]. Available: https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=SUMMARIES&countryabbv=&georegionabbv=&resolution=0. [Accessed: 25-Feb-2020].

[64] ASHRAE, *90.2 Energy-Efficient Design of Residential Low-Rise Buildings*. Atlanta, GA, 2018.

[65] U.S. Department of Energy, "Building Energy Codes Program," *TMY3 Weather Files*. [Online]. Available: https://www.energycodes.gov/development/commercial/prototype_models. [Accessed: 25-Feb-2020].

[66] ASHRAE, "Trends of Apparent Thermal Conductivity of Moist Soils," 2017th ed., 2017, p. Chapter 26.16, Section 4.7.

[67] U.S. Department of Energy, “ENERGY STAR Most Efficient 2020 - Geothermal Heat Pumps,” *Energy Efficient Products*, 2020. [Online]. Available: https://www.energystar.gov/products/energy_star_most_efficient_2020/geothermal_heat_pumps. [Accessed: 15-Feb-2020].

[68] Carrier Corporation, “GP Performance Series Geothermal Heat Pump Product Data,” Indianapolis, IN, 2016.

[69] Trane, “Geothermal / Water Source Heat Pump Product Data,” *Trane Prod. Data*, vol. 02-1853–01, 2011.

[70] ClimateMaster, “Tranquility ® 16 (TR) Series Submittal Data,” *Submitt. Data*, vol. 16, pp. 1–107, 2019.

[71] WaterFurnace, “Geothermal Packaged Outdoor Heat Pump,” *Specif. Cat.*, 2017.

[72] York Heating and Air Conditioning, “Geothermal Heat Pumps,” *Specif. Cat.*, 2018.

[73] EnergyPlus™, “Parametric Spreadsheets for Heat Pump Water-to-Water Water-to-Air,” 2017. [Online]. Available: http://energyplus.helpserve.com/Knowledgebase/Article/View/83/39/heatpump-watertowater-watertoair-spreadsheets-and-docs. [Accessed: 25-Feb-2020].

[74] M. Carvin and P. Camilleri, “Smart Asset,” 2019. [Online]. Available: https://smartasset.com/taxes/. [Accessed: 25-Feb-2020].

[75] S. Hanna, “Evaluation of Energy Saving Investments.pdf,” *J. Consum. Aff.*, vol. 12, no. 1, pp. 1–13, 1979.

[76] U.S. Energy Information Administration, “Electricity Data Browser,” *Independent Statistics & Analysis*, 2019. [Online]. Available: https://www.eia.gov/electricity/data/browser/. [Accessed: 25-Feb-2020].

[77] M. Sandoval, “Energy Policy Center Report : Electricity rates skyrocket across all Colorado sectors,” *Independence Institute*, Denver, CO, Mar-2016.

[78] U.S. Environmental Protection Agency, “A Guide to Energy-Efficient Heating and Cooling,” *EPA 430-K-09-004*.

[79] Electricity Local, “Local Electricity Rates and Statistics,” *Electricity Rates & Usage*, 2019. [Online]. Available: https://www.electricitylocal.com/. [Accessed: 25-Feb-2020].

[80] W. Wu and H. M. Skye, “Net-zero nation: HVAC and PV systems for residential net-zero energy buildings across the United States,” *Energy Convers. Manag.*, vol. 177, no. October, pp. 605–628, 2018.

[81] P. Torcellini, S. Pless, and M. Deru, "Zero Energy Buildings : A Critical Look at the Definition Preprint," in *American Council for an Energy-Efficient Economy (ACEEE) Summer Study*, 2006.

[82] J. Z. R. Neves, H. Cho, "State of the Nation: Customizing Energy and Finances for Geothermal Technology in the United States Residential Sector," *Renew. Sustain. Energy Rev.*, 2020.

[83] C. Christensen, R. Anderson, S. Horowitz, A. Courtney, and J. Spencer, "BEopt ™ Software for Building Energy Optimization : Features and Capabilities BEopt ™ Software for Building Energy Optimization : Features and Capabilities," 2006.

[84] C. B. Christensen and G. M. Barker, "Effects of tilt and azimuth on annual incident solar radiation for United States locations," in *Solar Forum 2001: Solar Energy: The Power to Choose*, 2015, no. January 2001.

[85] NC Clean Energy Technology Center, "DSIRE Programs." [Online]. Available: http://programs.dsireusa.org/system/program. [Accessed: 25-Feb-2020].

[86] J. Zhang, A. Knizley, and H. Cho, "Investigation of existing financial incentive policies for solar photovoltaic systems in US regions," *AIMS Energy*, no. 5, pp. 974–996, 2017.

[87] U.S. Department of Energy, "Florida Power and Light (FPL) Net Metering," *Energy Sage, Smarter Energy Decisions*, 2020. [Online]. Available: https://www.energysage.com/net-metering/fpl/. [Accessed: 21-Mar-2020].

[88] City of Gunnison Public Works Department, "Net Metering Program." Gunnison, CO, 2020.

[89] DSIRE NC Clean Energy Technology Center, "Arizona Net Metering Program Overview," 2020. [Online]. Available: https://programs.dsireusa.org/system/program/detail/3093. [Accessed: 21-Mar-2020].

[90] Tennessee Valley Authority, "Green Power Providers Program," 2020. [Online]. Available: https://www.tva.gov/Energy/Valley-Renewable-Energy/Green-Power-Providers/. [Accessed: 21-Mar-2020].

[91] NV Energy, "NV Energy Net Metering," 2020. [Online]. Available: https://www.nvenergy.com/account-services/energy-pricing-plans/net-metering/nmr-405. [Accessed: 21-Mar-2020].

[92] U.S. Department of Energy, "Los Angeles Department of Water and Power (LADWP) Net Metering," *Energy Sage, Smarter Energy Decisions*, 2020. [Online]. Available: https://www.energysage.com/net-metering/ladwp/. [Accessed: 21-Mar-2020].

[93] Baltimore Gas and Electric Company, “Solar Incentives & Rebates,” 2020. [Online]. Available: https://www.bge.com/SmartEnergy/MyGreenPowerConnection/Pages/FAQs.aspx.

[94] Portland General Electric, “No Title,” *Net Metering Billing*, 2020. [Online]. Available: https://www.portlandgeneral.com/residential/power-choices/renewable-power/install-solar-wind-more/net-metering/net-metering-billing. [Accessed: 21-Mar-2020].

[95] DSIRE NC Clean Energy Technology Center, “Des Moines Net Metering Program Overview,” *Net Metering*, 2020. [Online]. Available: https://programs.dsireusa.org/system/program/detail/488. [Accessed: 21-Mar-2020].

[96] DSIRE NC Clean Energy Technology Center, “Montana Net Metering Program Overview,” *Net Metering*, 2020. [Online]. Available: https://programs.dsireusa.org/system/program/detail/37. [Accessed: 21-Mar-2020].

[97] Minnesota Public Utilities Commision, “Net Metering & Compensation,” *Net Metering & Compensation*, 2020. [Online]. Available: https://mn.gov/puc/energy/distributed-energy/net-metering/. [Accessed: 21-Mar-2020].

[98] National Renewable Energy Laboratory, “U.S State Solar Resource Maps,” *Geospatial Data Science*, 2020. [Online]. Available: https://www.nrel.gov/gis/solar.html. [Accessed: 06-Jan-2020].

[99] L. M. Arpan, X. Xu, A. A. Raney, C. Chen, and Z. Wang, “Politics , values , and morals : Assessing consumer responses to the framing of residential renewable energy in the United States,” *Energy Res. Soc. Sci.*, vol. 46, no. August, pp. 321–331, 2018.

[100] J. Haidt and C. Joseph, “Intuitive Ethics: How Innately Prepared Intuitions Generate Culturally Variable Virtues,” *Deadalus*, no. Fall 2004, pp. 55–66, 2004.

[101] M. Feinberg and R. Willer, “The Moral Roots of Environmental Attitudes,” *Psychol. Sci.*, vol. 24, pp. 56–62, 2013.

[102] G. Perlaviciute and L. Steg, “The influence of values on evaluations of energy alternatives,” *Renew. Energy*, vol. 77, pp. 259–267, 2015.

APPENDIX A

CITY SELECTION DATA WITH MAPS SHOWING AREA OF INTEREST AND TEMPERATURE / HUMIDITY DIVERSITY PROFILES

A.1 Temperature / Humidity Diversity Profiles

Figure A.1 and Figure A.2 complement Figure 3.5 and Figure 3.6 by showing the same information in two different graphic forms. Both representation aim to display the diversity of 12 cities in terms of temperature and average annual relative humidity.

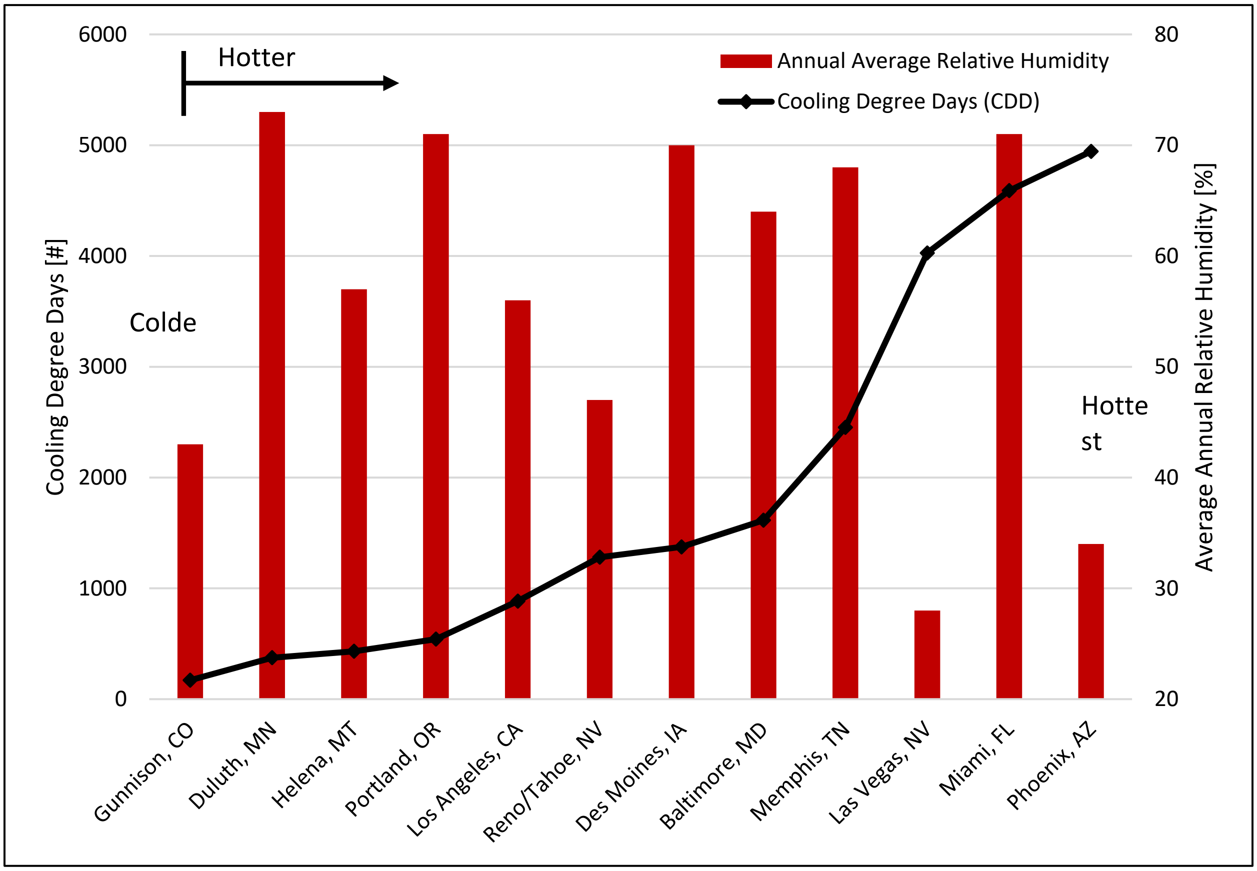

Figure A.1 CDD and Humidity Diversity by City

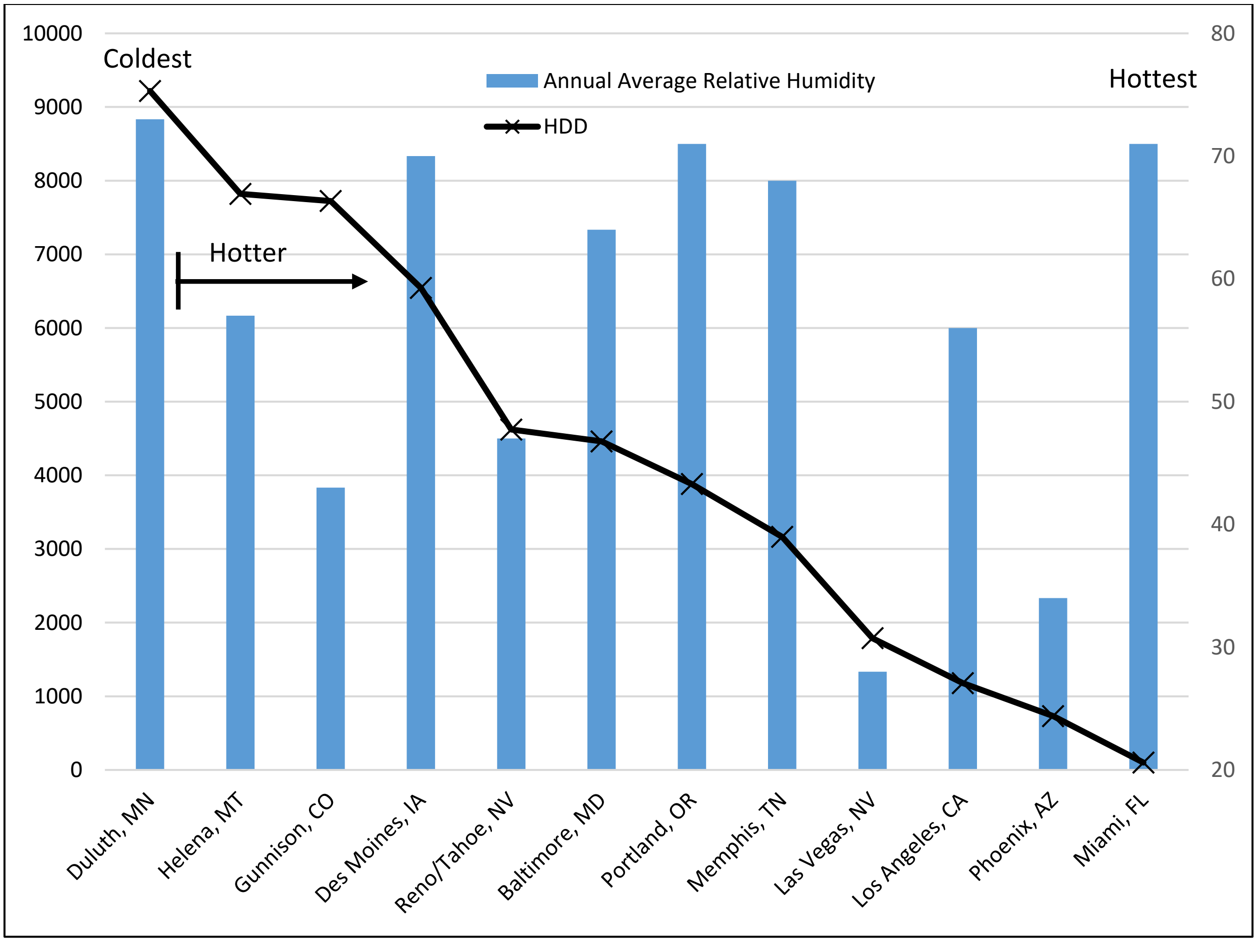

Figure A.2 HDD and Humidity Diversity by City

A.2 Area of Interest (AOI) Maps

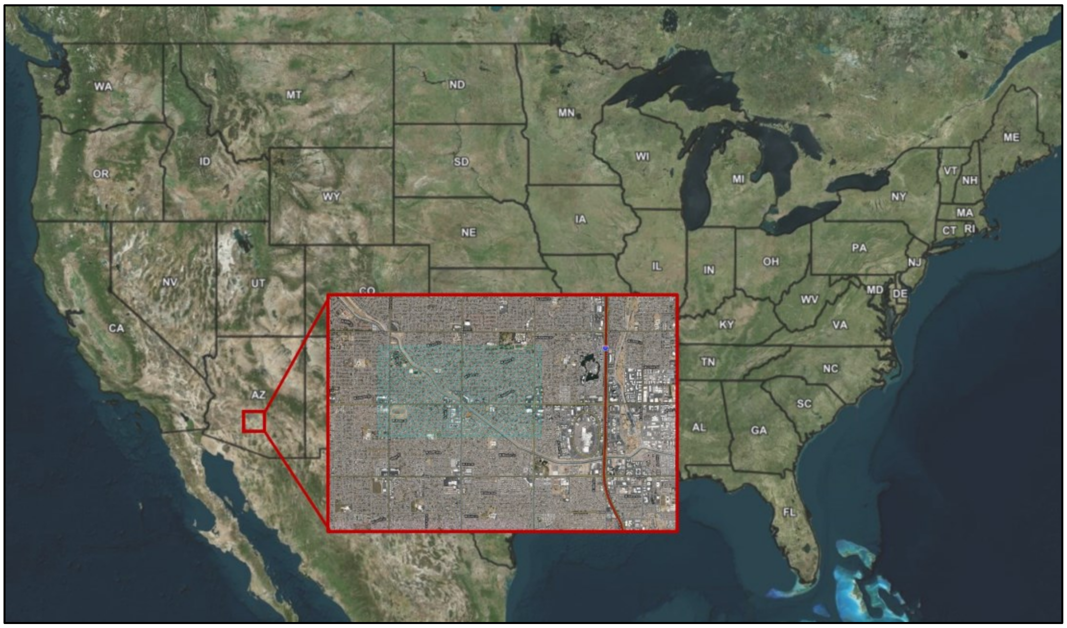

Figure A.3 AOI Map of Phoenix, AZ

Actual address is Street, Zip Code: W Camino Acequia, 33150

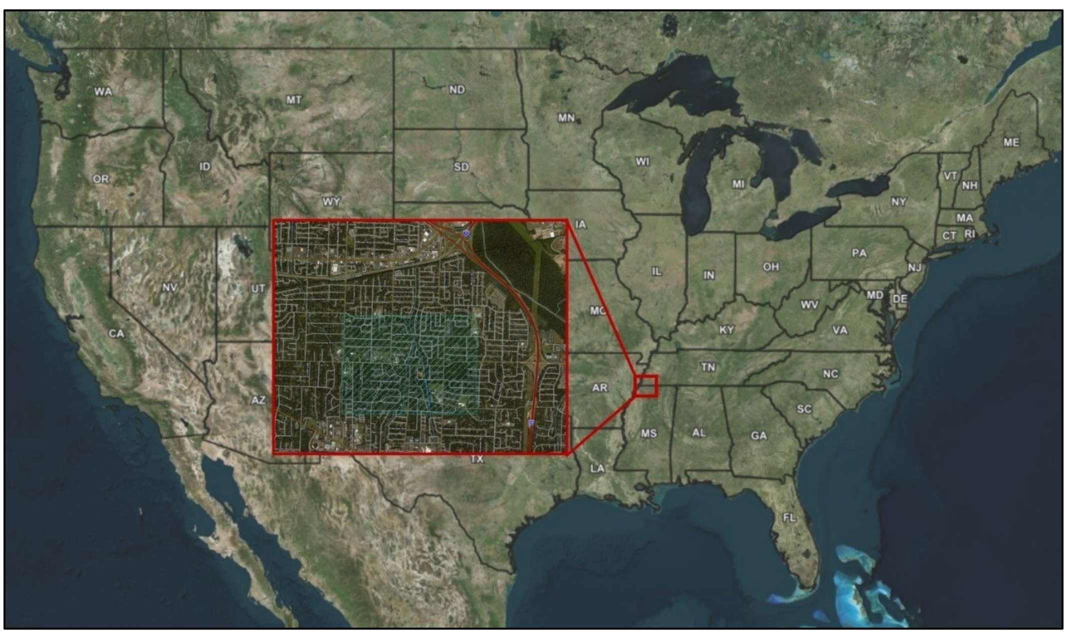

Figure A.4 AOI Map of Memphis, TN

Actual address is Street, Zip Code: N Angela Road, 38117

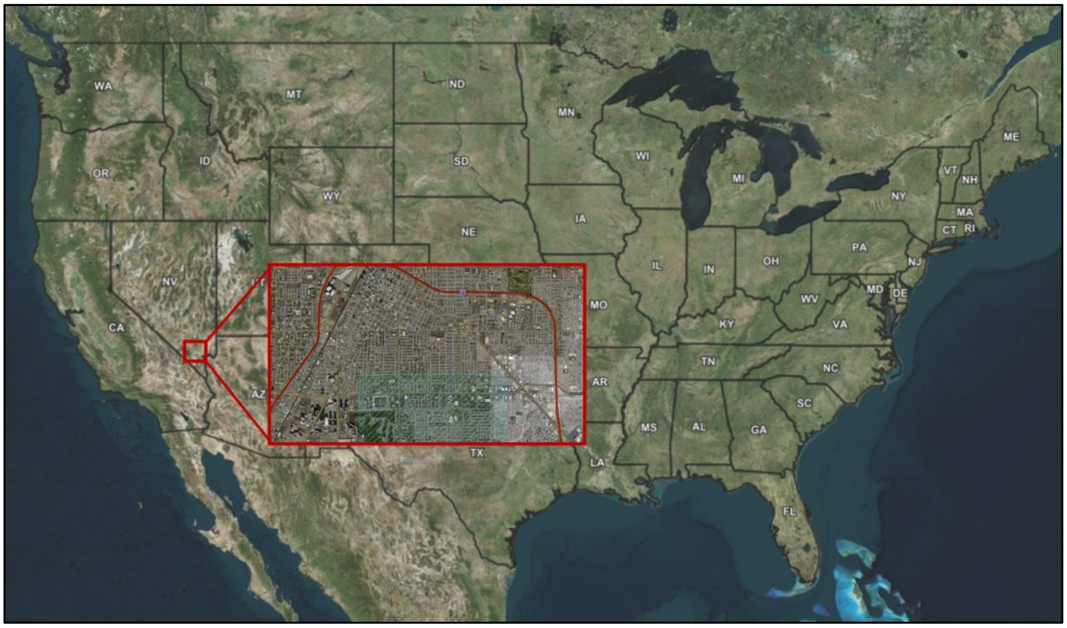

Figure A.5 AOI Map of Las Vegas, NV

Actual address is State, Zip Code: Capistrano Avenue, 89169

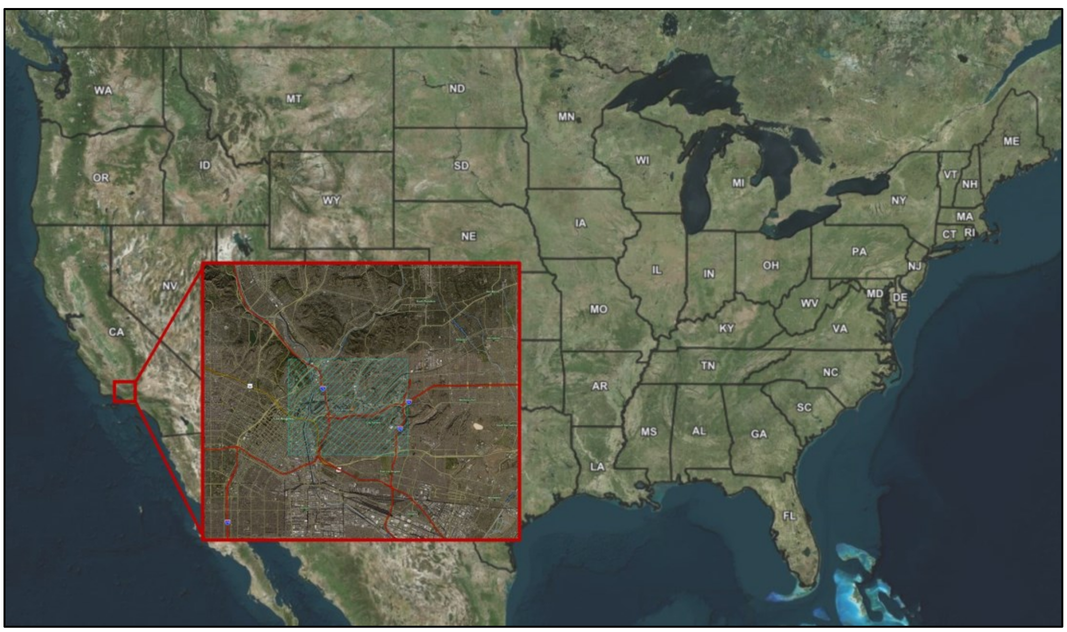

Figure A.6 AOI for Los Angeles, CA

Actual address is State, Zip Code: Lancaster Avenue, 90033

Figure A.7 AOI Map for Baltimore, MD

Actual address is State, Zip Code: Kildaire Drive, 21234

Figure A.8 AOI Map for Portland, OR

Actual address is State, Zip Code: NE 35th Avenue, 97212

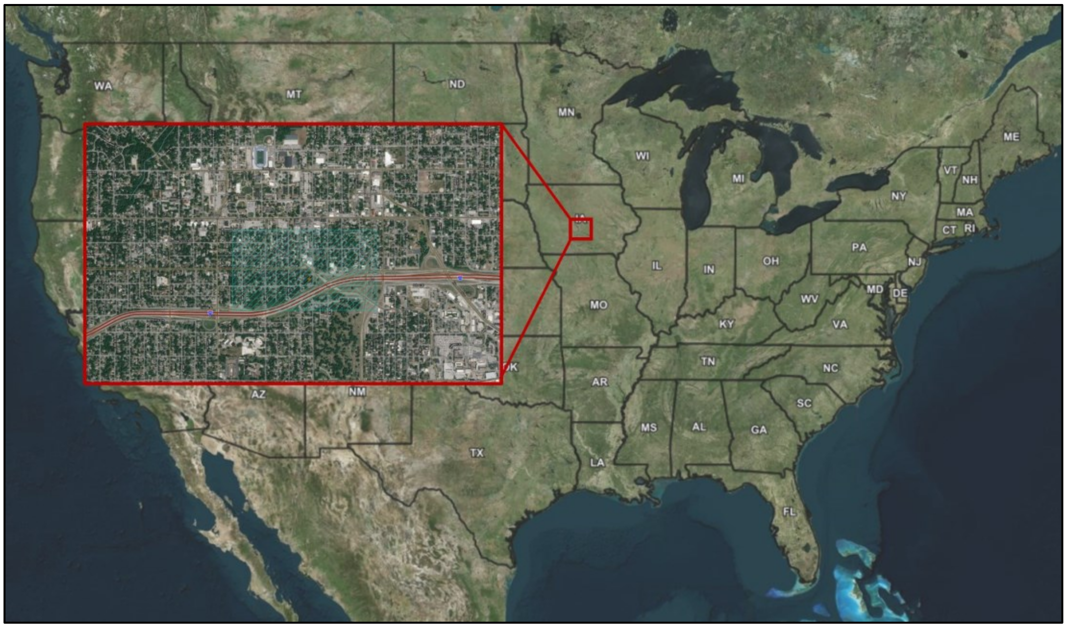

Figure A.9 AOI Map for Des Moines, IA

Actual address is State, Zip Code: 24th Street, 50311

Figure A.10 AOI Map for Reno, NV

Actual address is State, Zip Code: Shale Court, 89503

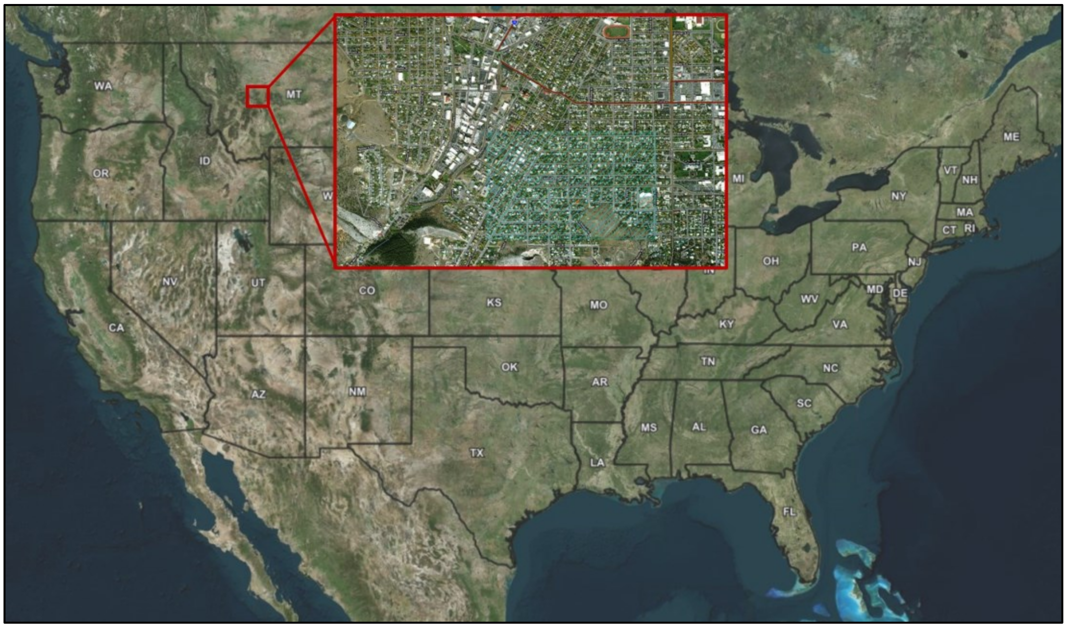

Figure A.11 AOI Map for Helena, MT

Actual address is State, Zip Code: Hillsdale Street, 59601

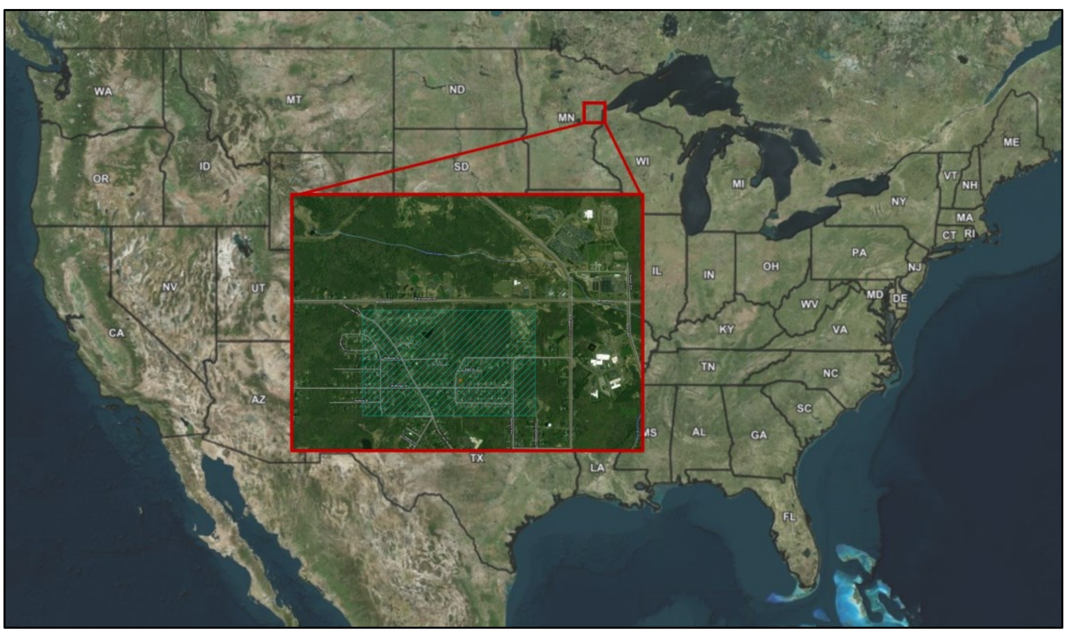

Figure A.12 AOI Map for Duluth, MN

Actual address is State, Zip Code: N Robin Avenue, 55811

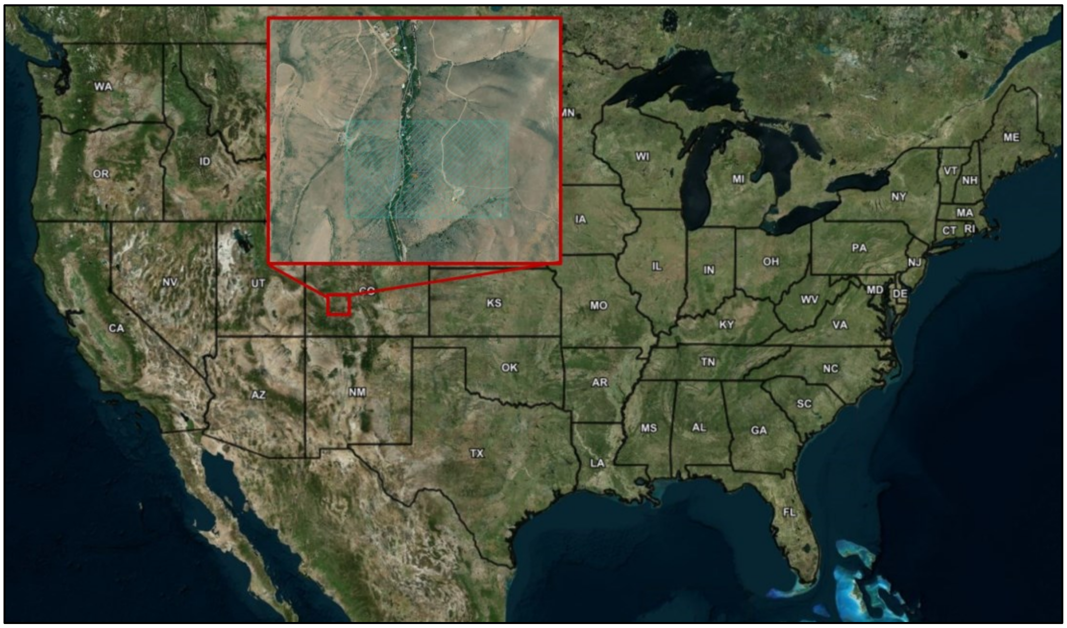

Figure A.13 AOI Map for Gunnison, CO

Actual address is State, Zip Code: County Road 20, 81230

APPENDIX B

ENERGYPLUS™ HEAT PUMP PERFORMANCE COEFFICIENT GENERATOR METHOD

AND SUPPORTING DATA AND FILES

B.1 Heat Pump Coefficient Generation Data

Table B.1 EnergyPlus™ Input Heat Pump Performance Coefficients

	HP024		*HP036*		*HP048*	
	Cooling Coil	Heating Coil	Cooling Coil	Heating Coil	Cooling Coil	Heating Coil
1	-4.90456531	-2.31799810	-5.33174458	-2.23147019	-5.18481347	-2.57816437
2	6.74327980	-0.78825906	7.06259528	-0.79543561	7.19541141	-0.57868509
3	-1.45210858	3.50281385	-1.30151223	3.71116372	-1.51151664	3.65509182
4	0.25233643	0.227169696	0.16321878	-0.07476022	0.09149811	0.06732808
5	-0.042760421	0.067085681	0.009486198	0.079757167	0.026531282	0.137729839
6	1.50250021	-5.57554629	3.13537550	-3.70705061	0.13464599	-4.43776197
7	21.27852024	4.91536758	30.99145717	3.39233638	18.65343886	3.92433630
8	-22.30015882	1.30587064	-34.07154422	1.51413262	-18.43628448	1.45412049
9	-0.70887544	0.093056981	-0.47494141	-0.537282926	-0.58733449	-0.214467208
10	0.618561893	-0.051125447	0.53647961	-0.01329062	0.652992841	0.022058736
11	-0.02998072		0.080077076		-0.062089624	
12	-8.33369971		-6.72197223		-5.70232299	
13	2.53386728		1.91664373		0.27881283	
14	6.16096323		6.20129177		7.13878521	
15	0.68967646		-0.36306207		-0.45105570	
16	-0.220149668		-0.256439687		-0.272224773	

B.1.1 Cooling Coefficients Spreadsheet: General 2-ton Geothermal Heat Pump

The following spreadsheet contains contains compiled heat pump performance data for five manufacturers and the resulting EnergyPlus™ heat pump coefficients for a 2-ton heat pump cooling coil. WaterAir_PE_Cooling 024 – Combined

B.1.2 Heating Coefficients Spreadsheet: General 2-ton Geothermal Heat Pump

The following spreadsheet contains contains compiled heat pump performance data for five manufacturers and the resulting EnergyPlus™ heat pump coefficients for a 2-ton heat pump heating coil. WaterAir_PE_Heating 024 – Combined

B.1.3 Cooling Coefficients Spreadsheet: General 3-ton Geothermal Heat Pump

The following spreadsheet contains contains compiled heat pump performance data for five manufacturers and the resulting EnergyPlus™ heat pump coefficients for a 3-ton heat pump cooling coil. Access file here: WaterAir_PE_Cooling 036 – Combined

B.1.4 Cooling Coefficients Spreadsheet: General 3-ton Geothermal Heat Pump

The following spreadsheet contains contains compiled heat pump performance data for five manufacturers and the resulting EnergyPlus™ heat pump coefficients for a 3-ton heat pump heating coil. Access file here: WaterAir_PE_Heating 036 – Combined

B.1.5 Cooling Coefficients Spreadsheet: General 4-ton Geothermal Heat Pump

The following spreadsheet contains contains compiled heat pump performance data for five manufacturers and the resulting EnergyPlus™ heat pump coefficients for a 3-ton heat pump cooling coil. Access file here: WaterAir_PE_Cooling 048 – Combined

B.1.6 Cooling Coefficients Spreadsheet: General 4-ton Geothermal Heat Pump

The following spreadsheet contains contains compiled heat pump performance data for five manufacturers and the resulting EnergyPlus™ heat pump coefficients for a 2-ton heat pump cooling coil. Access file here: WaterAir_PE_Heating 048 – Combined

B.2 Soil and Incentive Parameters by City

Table B.2 Soil and Incentive Parameters by City

Zone	**City | State**	**Zip Code**	***k* [W/m•K]**	**Percent Discount**	***i* Multiplier**
1A	Miami | FL	33150	1.586	0.0112	0.08
2B	Phoenix | AZ	85051	1.442	0.0327	0.23
3A	Memphis | TN	38117	2.307	0.0287	0.20
3B	Las Vegas | NV	89169	1.730	0.0000	0.00
3C	Los Angeles | CA	90033	1.009	0.0930	0.66
4A	Baltimore | MD	21234	2.163	0.1086	0.77
4C	Portland | OR	97212	2.163	0.0133	0.09
5A	Des Moines | IA	50311	1.730	0.1402	1.00
5B	Reno | NV	89503	2.307	0.0000	0.00
6B	Helena | MT	59601	1.586	0.0932	0.66
7A	Duluth | MN	55811	1.298	0.0121	0.09
7B	Gunnison | CO	81230	2.307	0.0025	0.02